

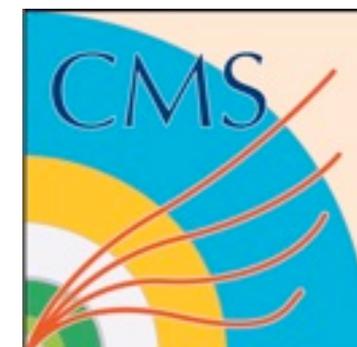
The Future of Boosted Top Quarks

S. Chekanov, J. Dolen, J. Pilot, R. Poeschl, B. Tweedie

Top & Detectors Working Group

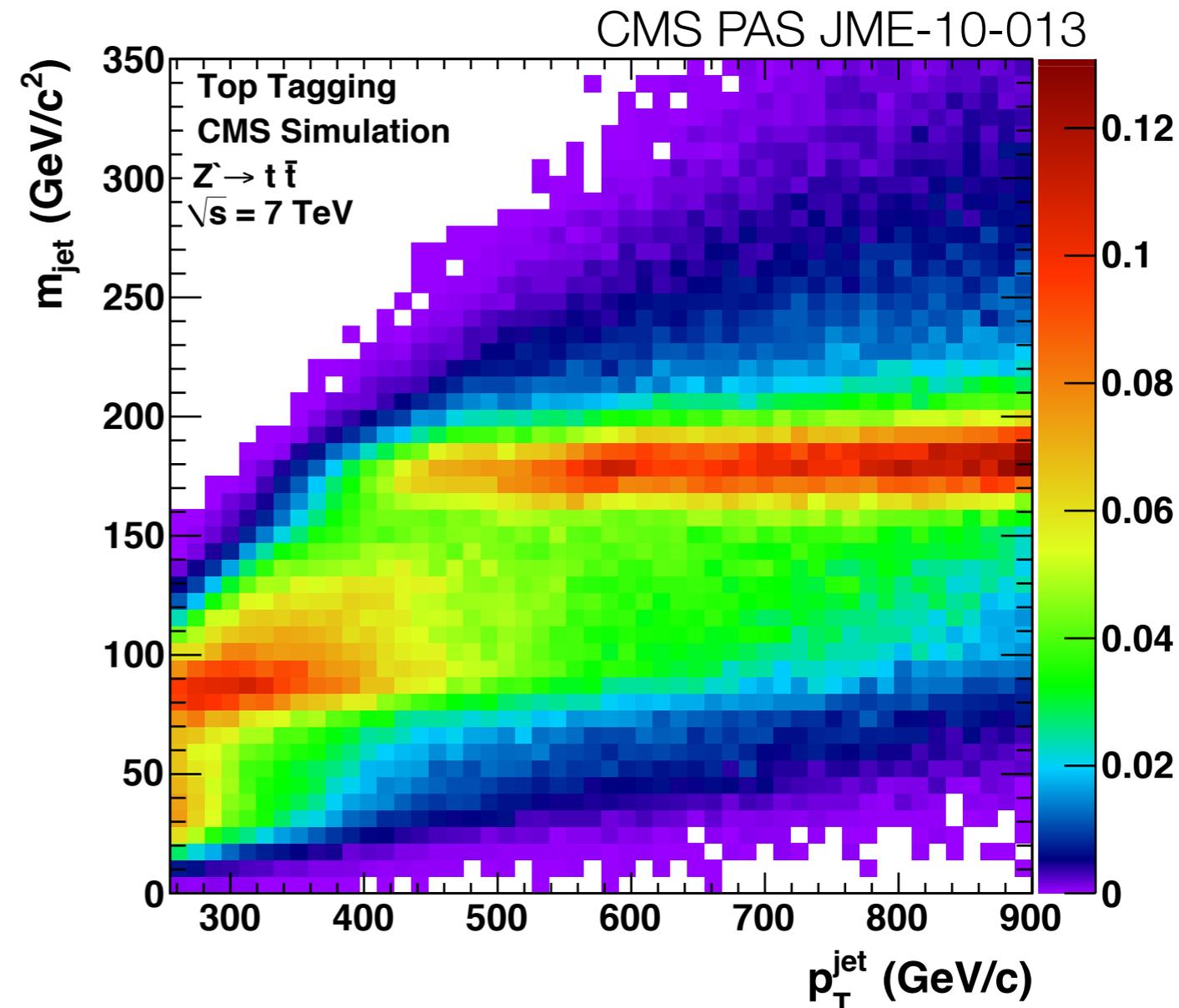
Snowmass Energy Frontier Meeting

5 April 2013



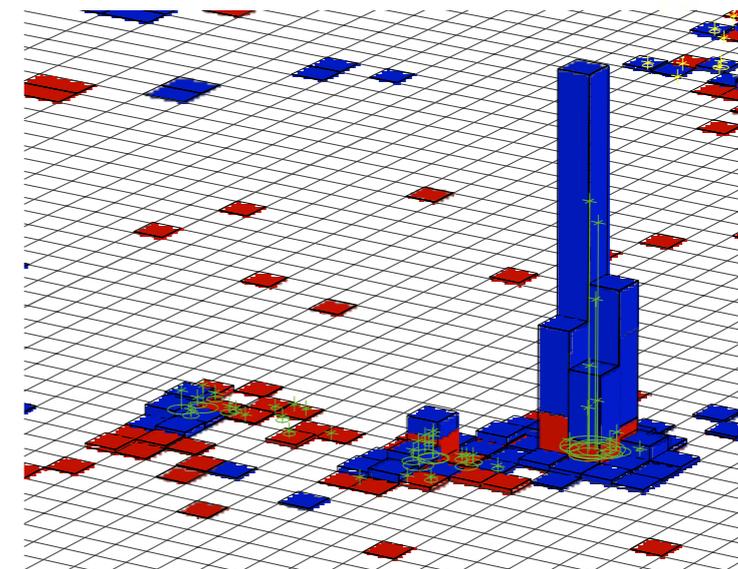
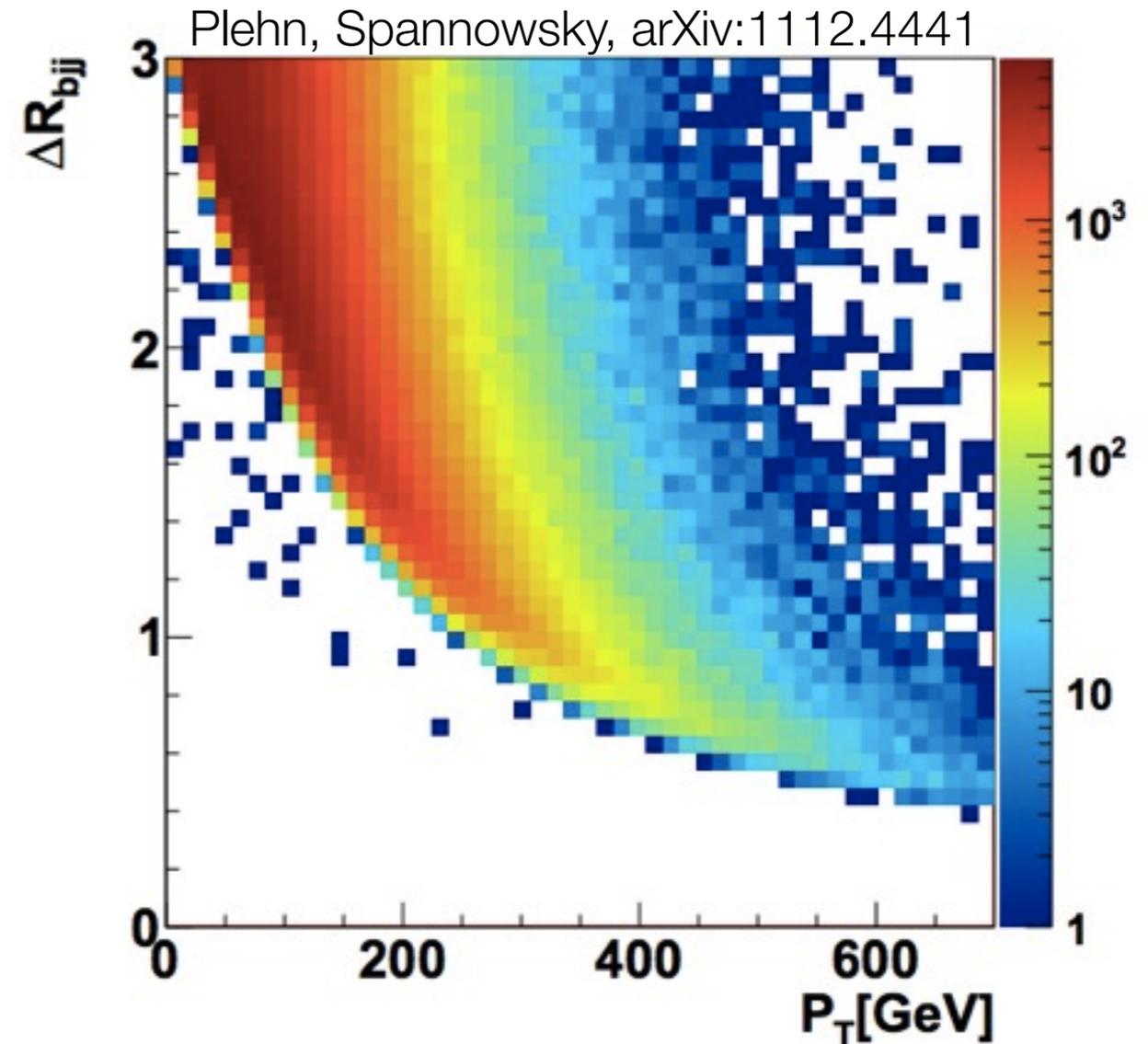
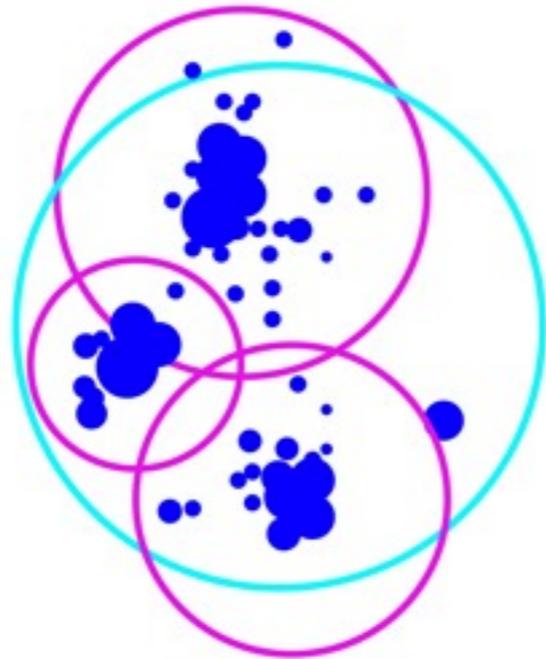
Introduction

- ▶ As collision energies increase, particles are produced with higher p_T
 - ▶ **Boosted regime**
- ▶ To maintain efficiency for selecting certain physics processes, new techniques required
 - ▶ **Jet substructure**
 - ▶ Used for reconstruction of boosted W, Z, H bosons, **top quarks**
- ▶ How well can we reconstruct such objects?
- ▶ Can we maintain this reconstruction going to higher energies?
 - ▶ What about pileup?
- ▶ Where do the current methods break down and what are the next steps?



Boosted Top Quarks

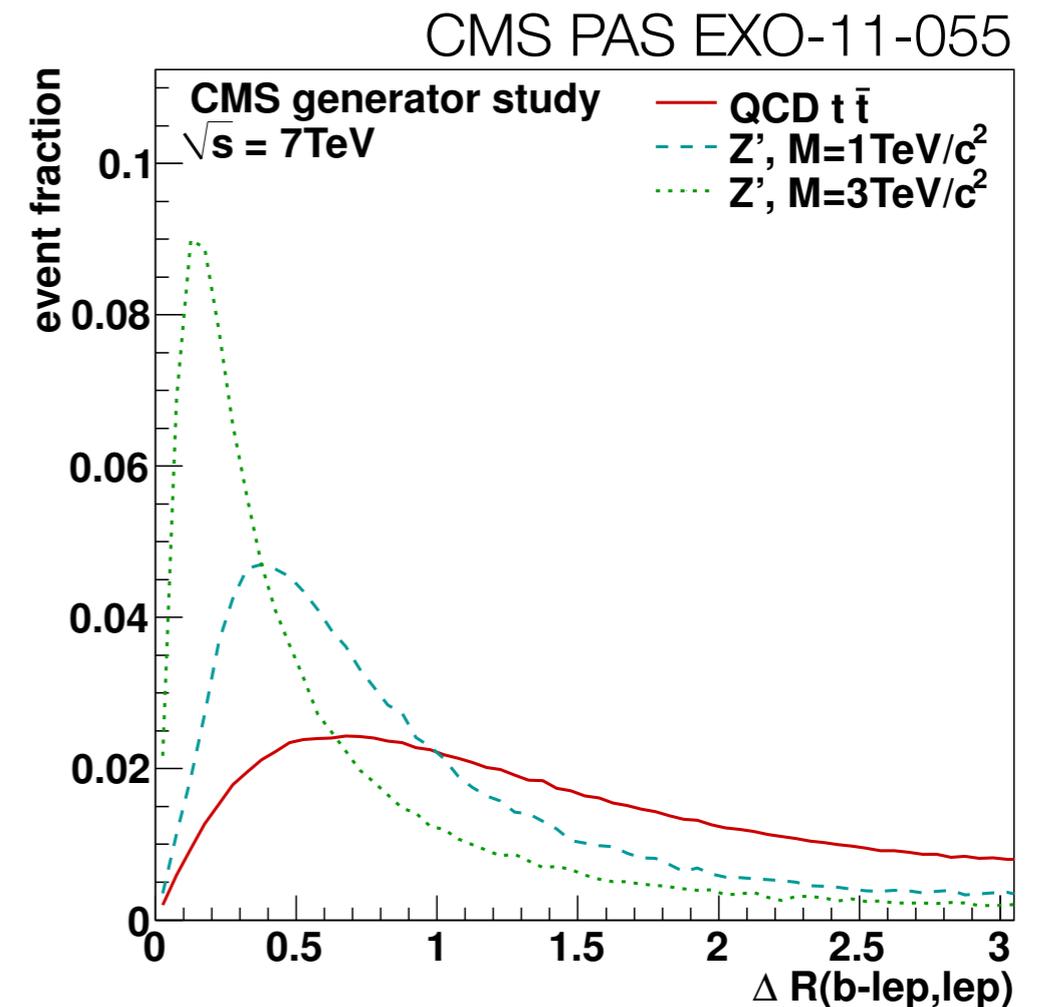
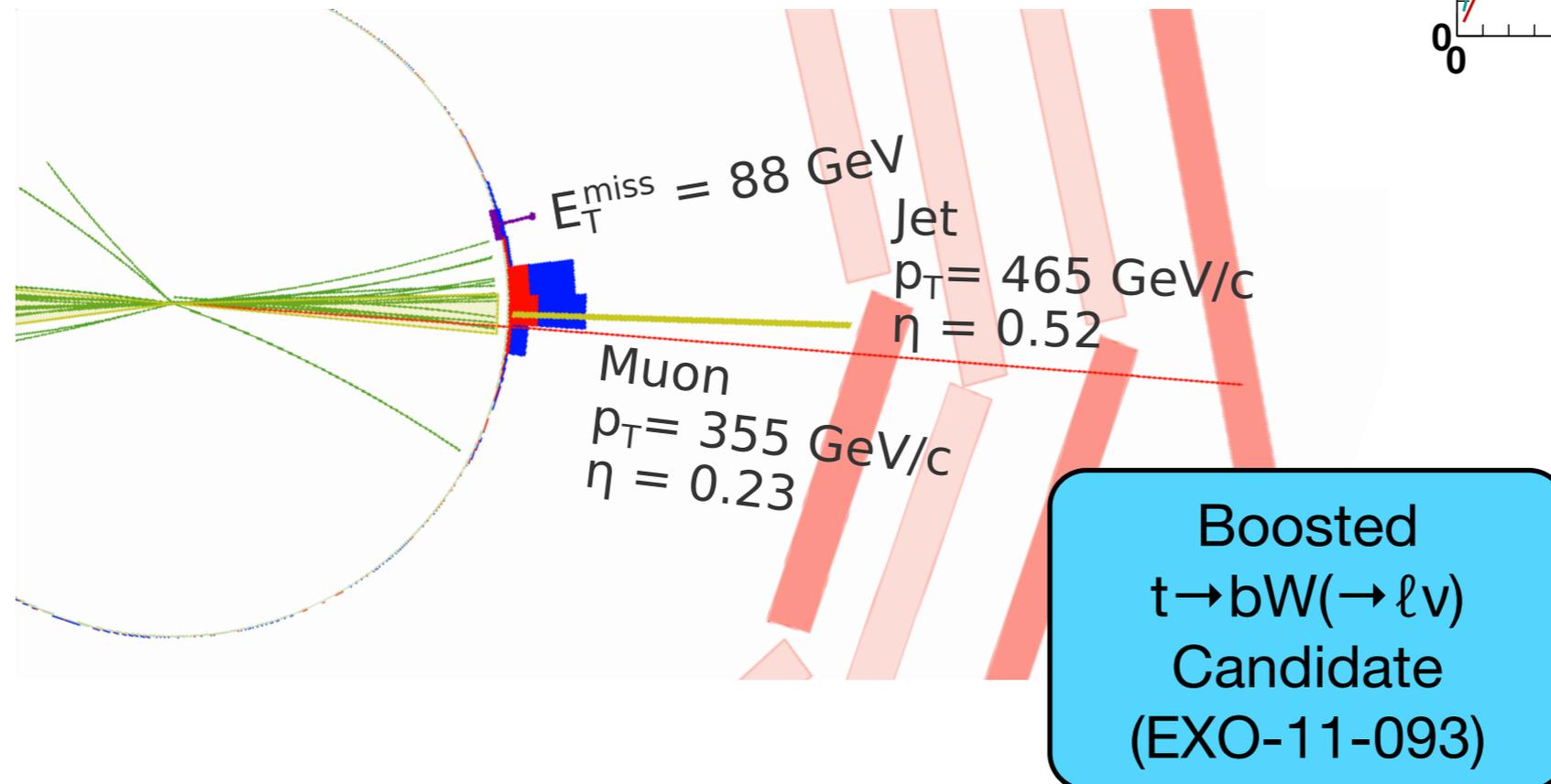
- ▶ For top quarks with $p_T > 500$ GeV, the decay products will merge into a single jet
 - ▶ Choose cone size to 'catch' all decay products
- ▶ Typically then look within the single jet to find structure corresponding to decay products
- ▶ At extreme boosts, the decay products will be highly collimated
 - ▶ Prefer high detector granularity to resolve individual energy deposits



CMS EXO-11-006

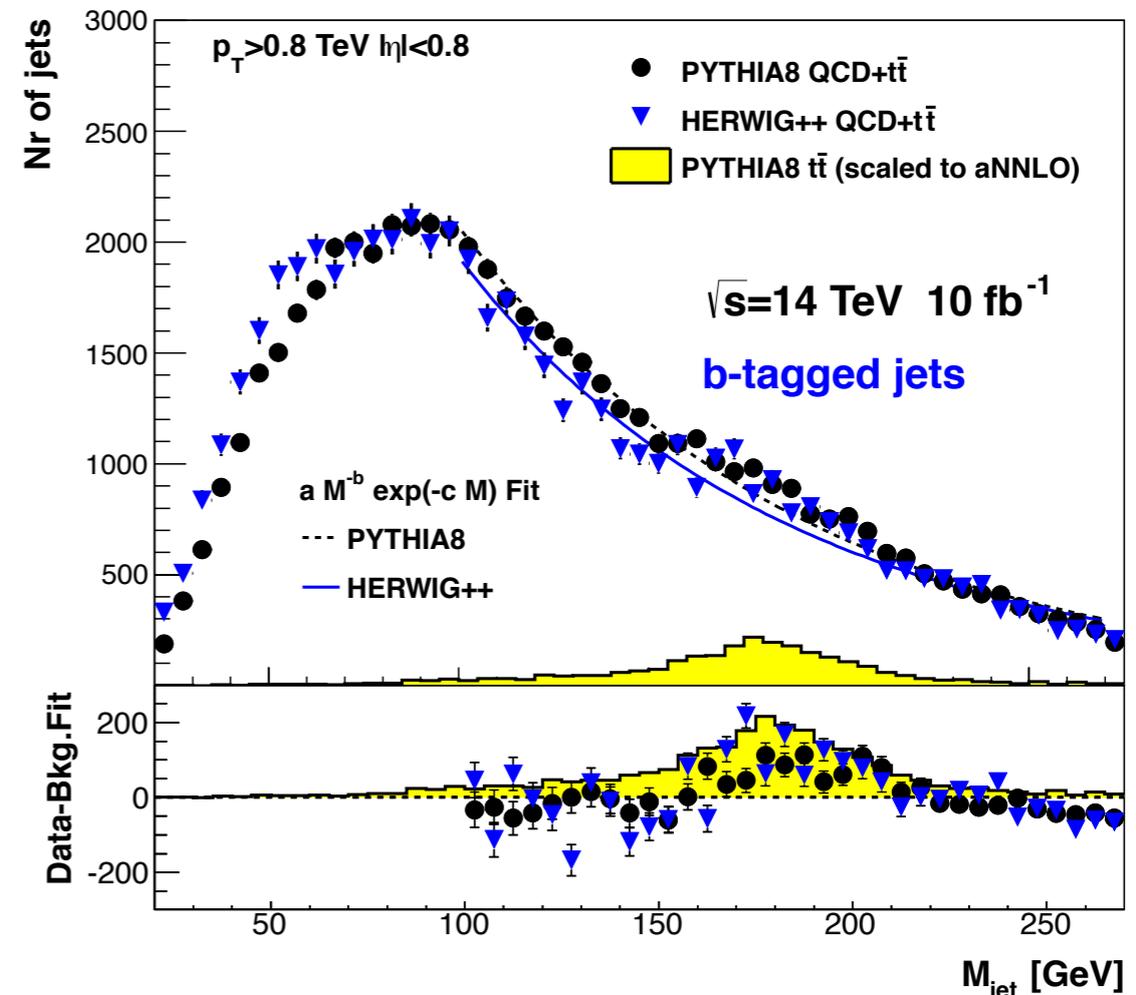
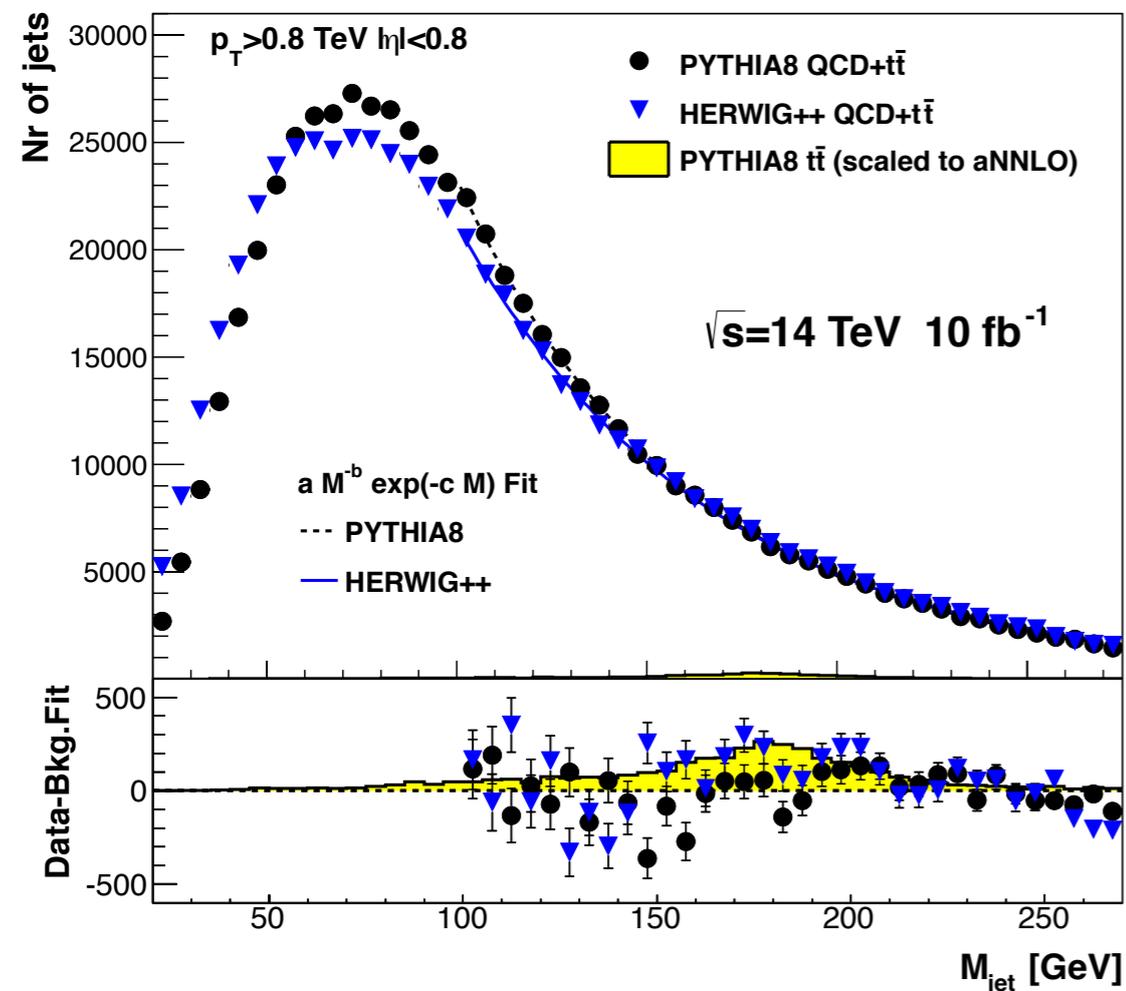
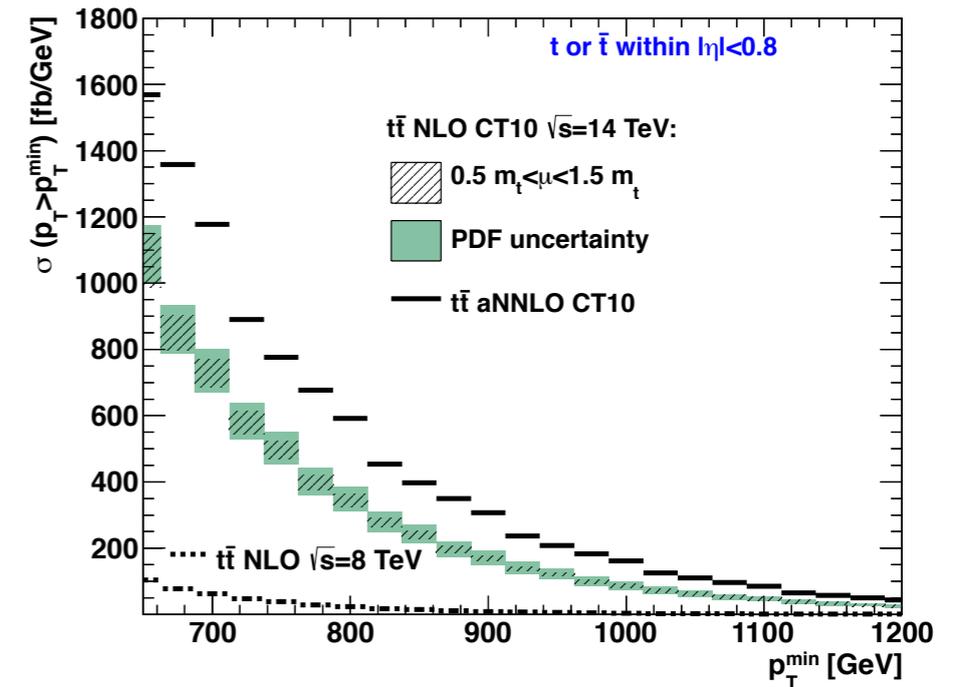
Leptonic Decays

- ▶ Boosted techniques also useful in lepton+jets topology
- ▶ Lepton, b-jet from top decay collinear
 - ▶ Worry about contamination of lepton isolation
- ▶ Need special criteria to avoid vetoing these events



Inclusive Jet Mass

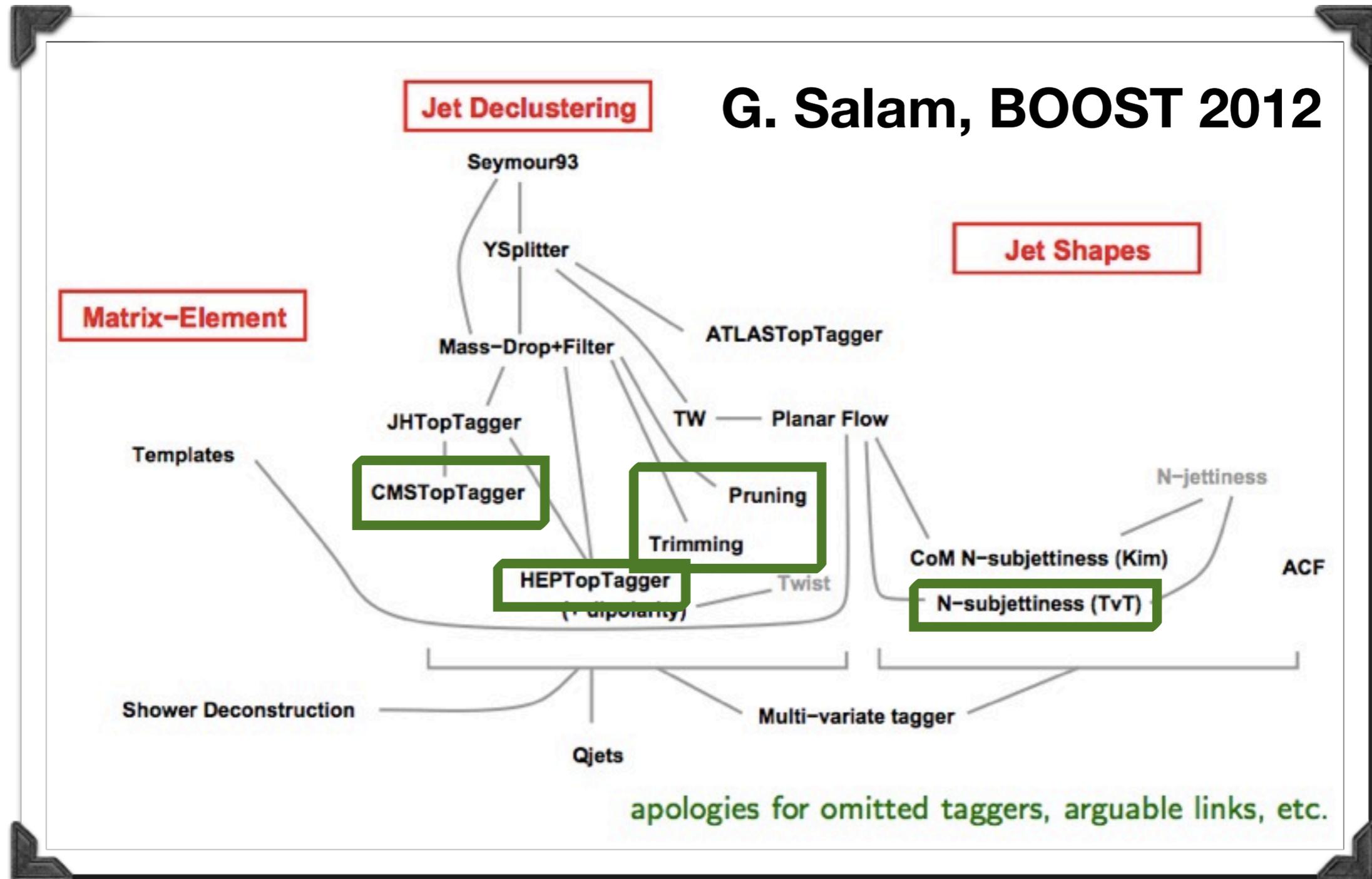
- ▶ Possibility to probe top in the inclusive jet mass spectrum
 - ▶ Increasing cross section with NNLO corrections
- ▶ Can probe new physics models through limits on $t\bar{t}$ cross section alone
 - ▶ Discrimination could be further enhanced with substructure observables!



Algorithm Development

- ▶ Many ideas in use or under development presently

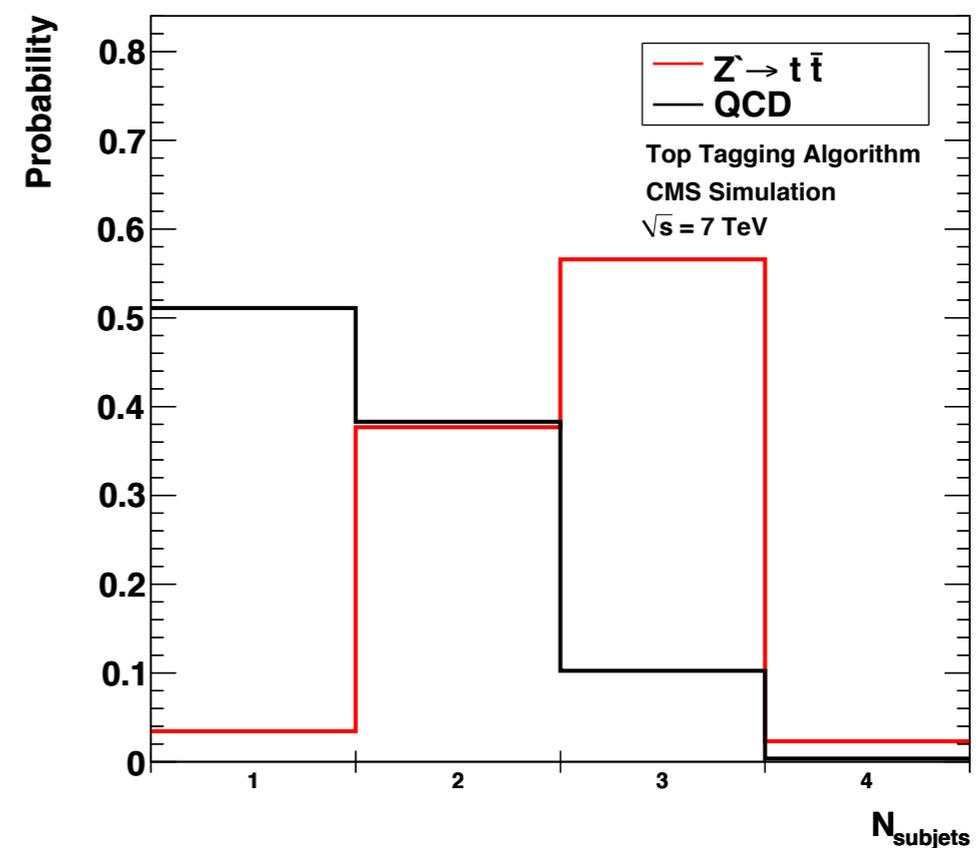
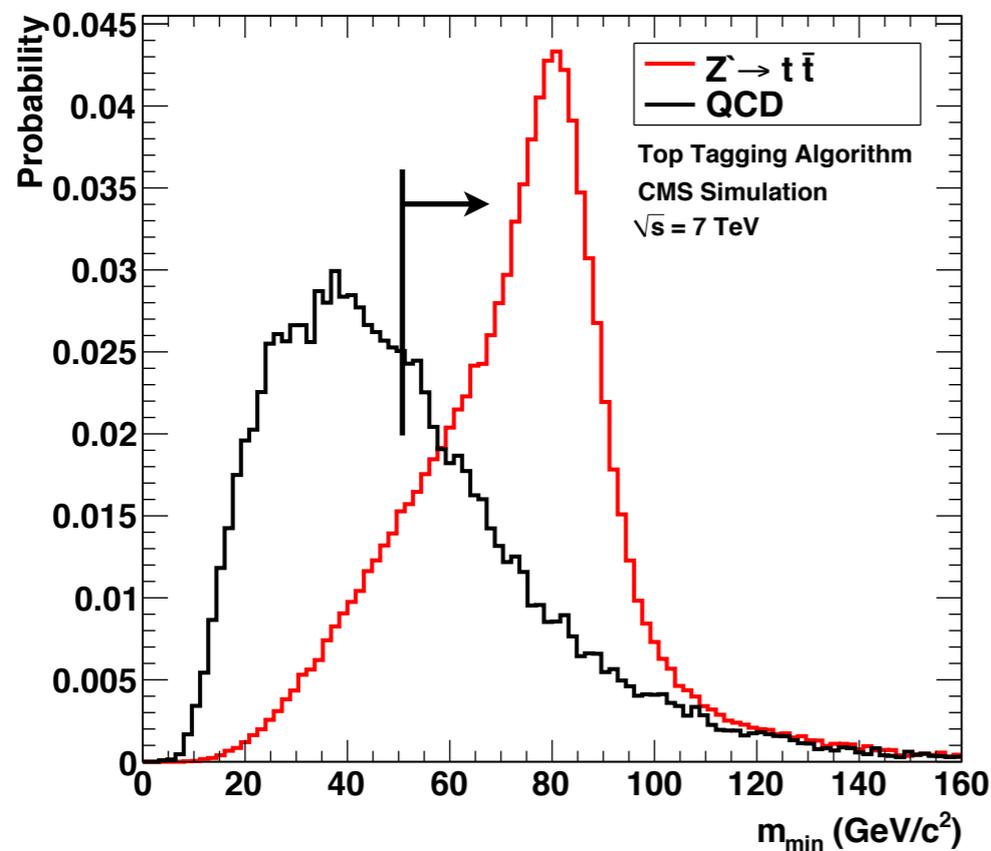
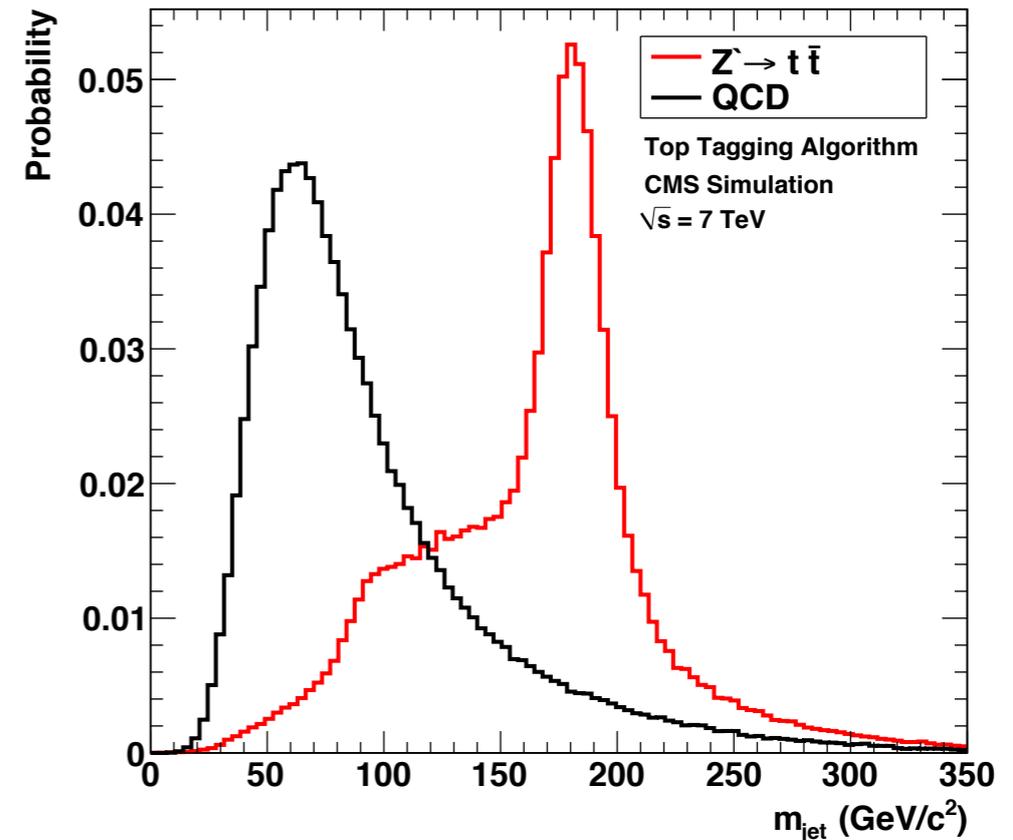
- ▶ Will touch on a few specific examples



Top Tagging Algorithms

CMS PAS JME-10-013

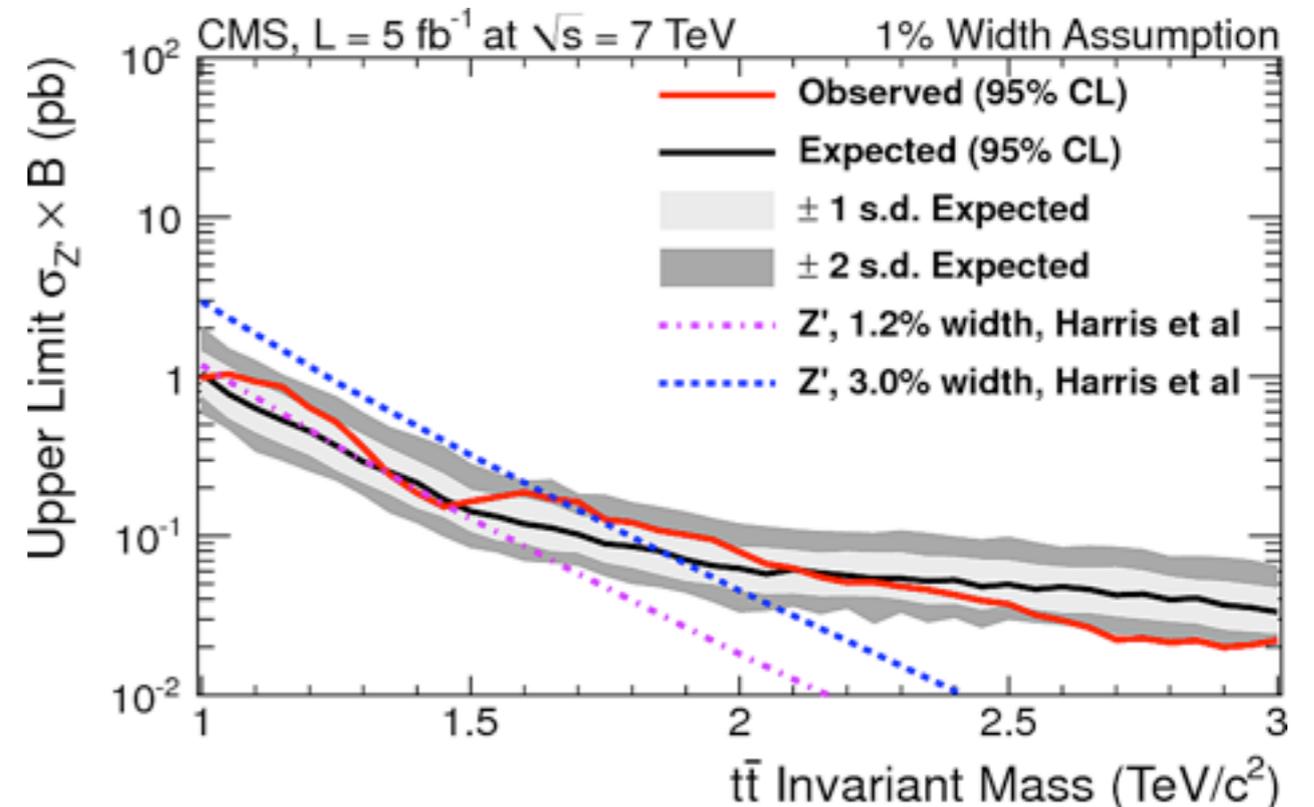
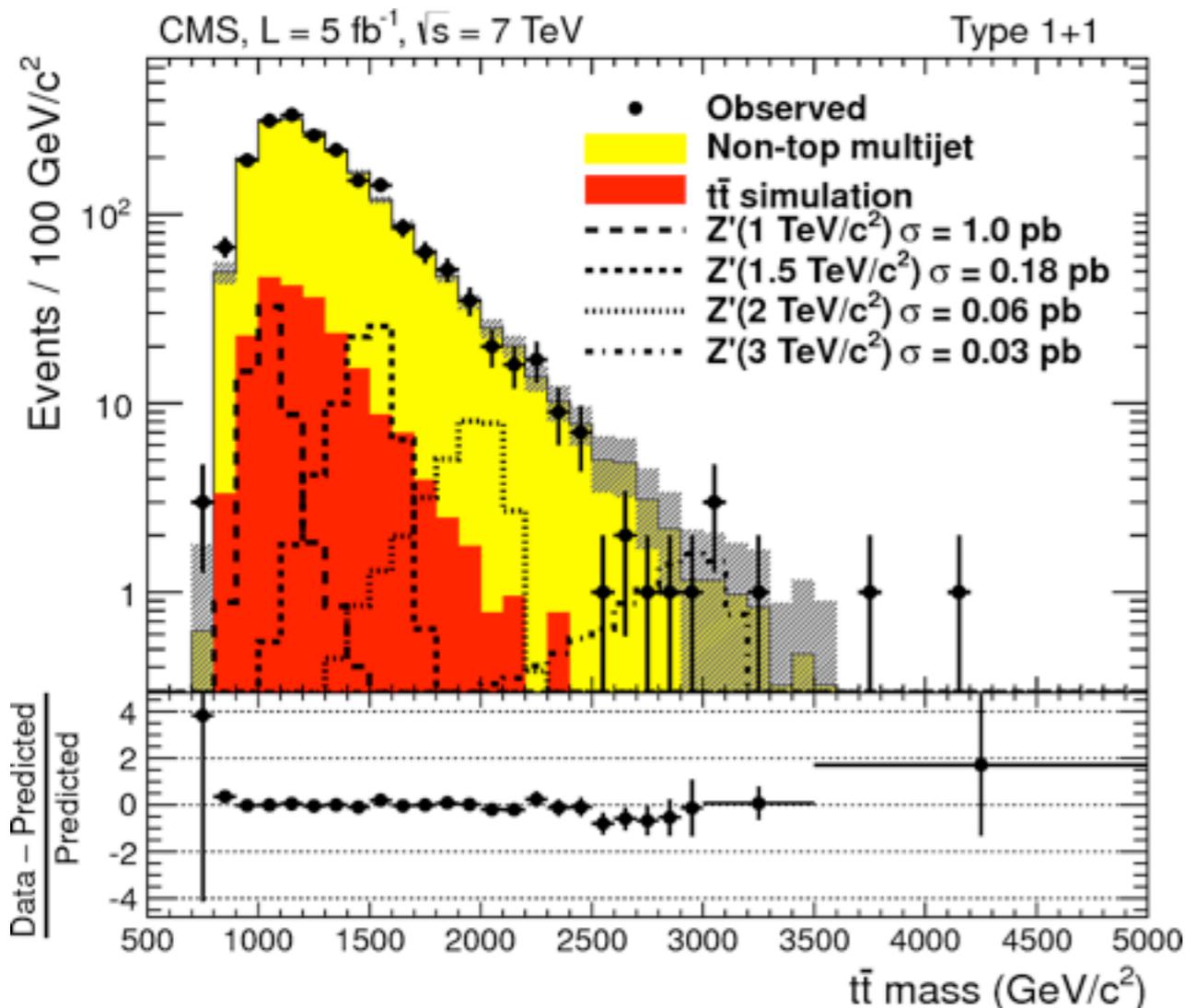
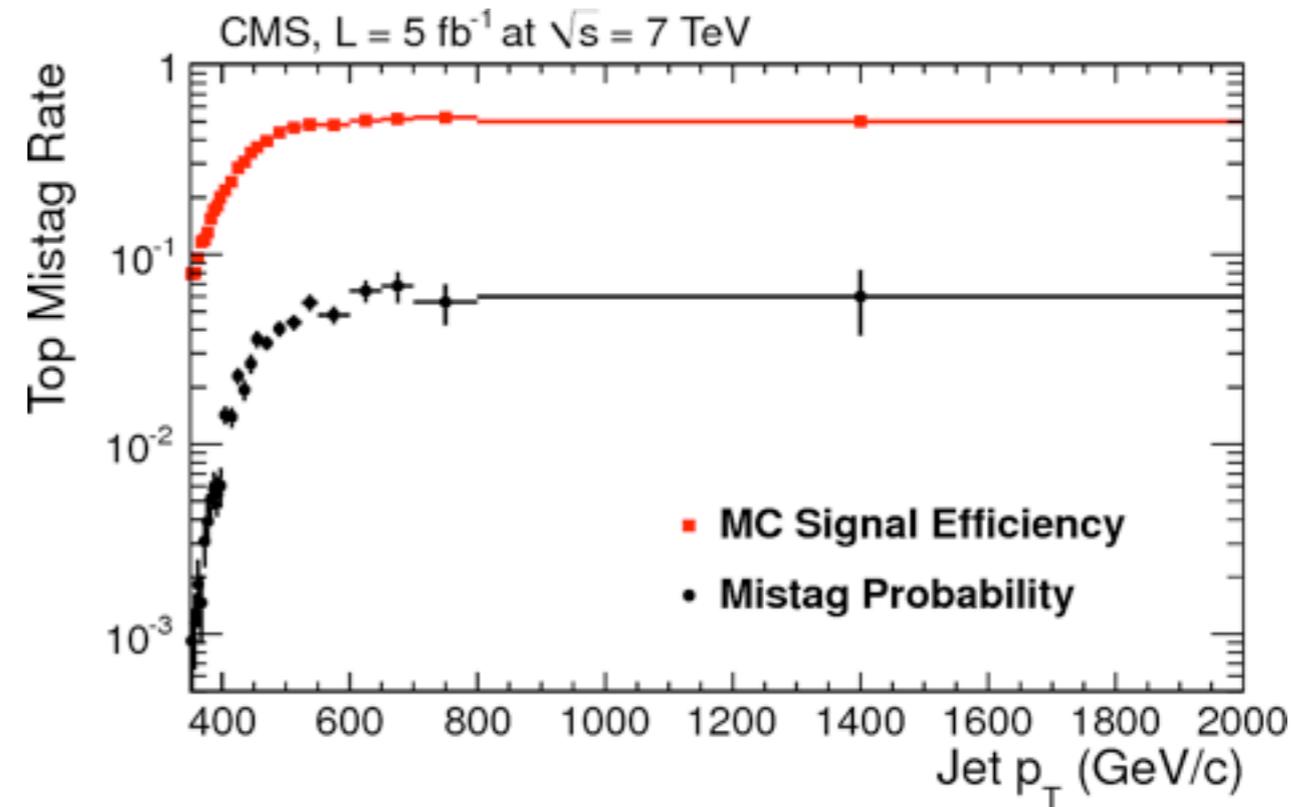
- ▶ CMS Top Tagger in use
 - ▶ Declusters jets (Cambridge-Aachen $R = 0.8$) to find substructure
 - ▶ Requirements on substructure quantities:
 - ▶ ≥ 3 subjets
 - ▶ Jet mass consistent with top mass $[140, 250]$ GeV
 - ▶ Identification of a W boson candidate using minimum pairwise subjet mass



CMS Top Tagger

CMS EXO-11-006,
arXiv: 1204.2488

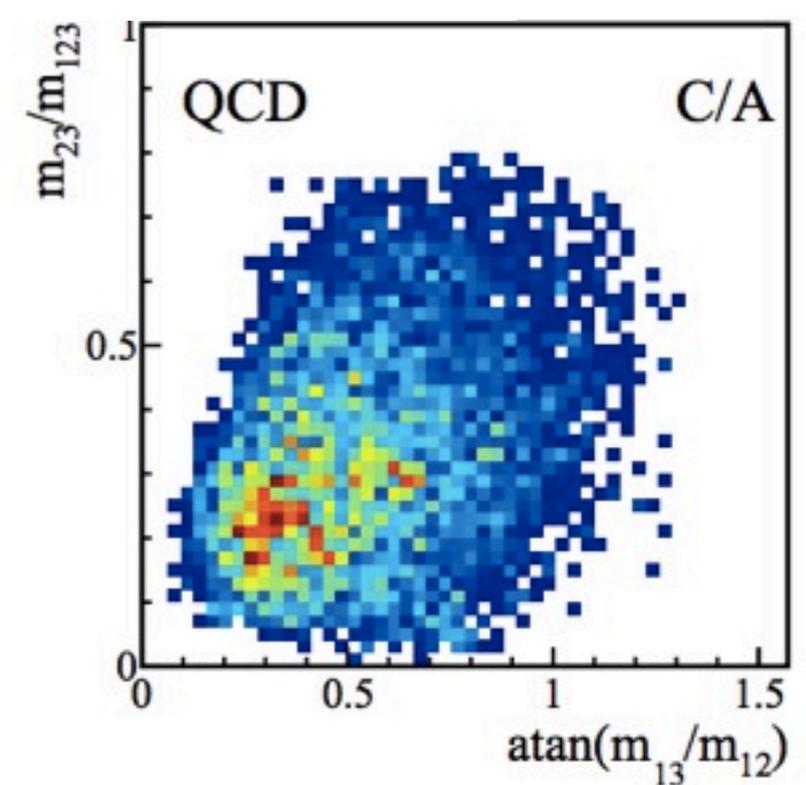
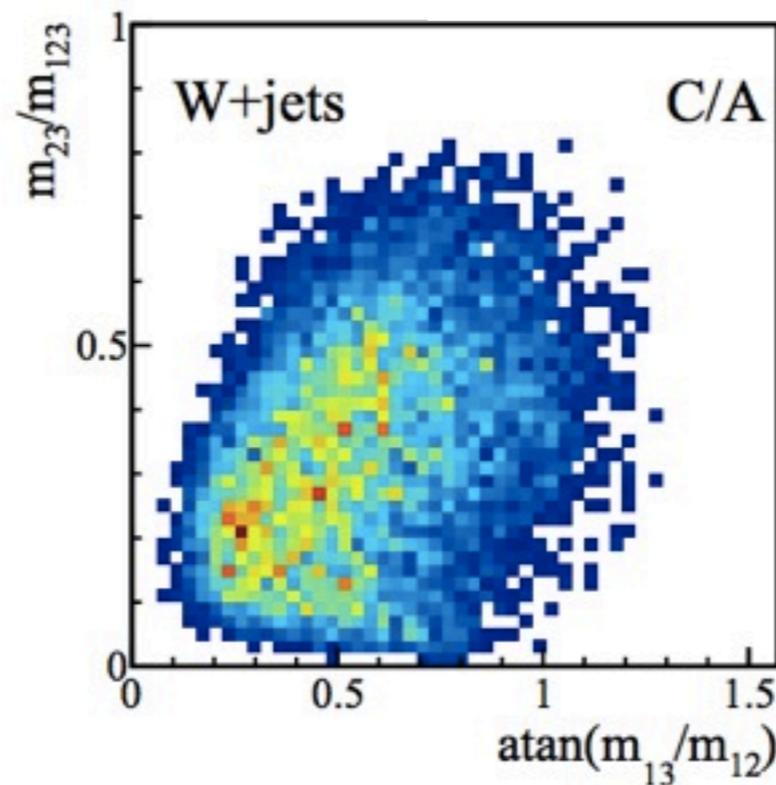
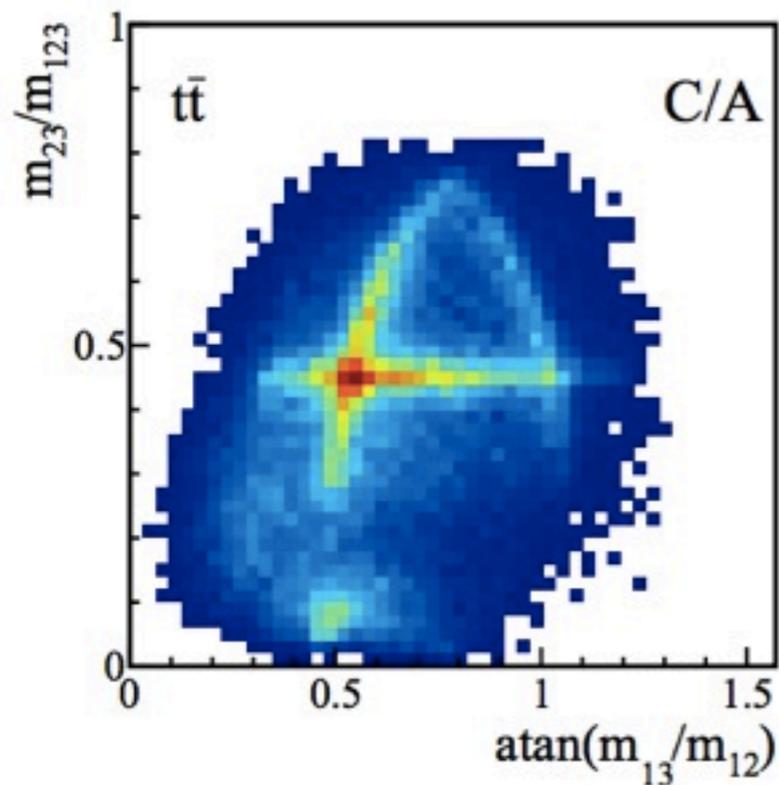
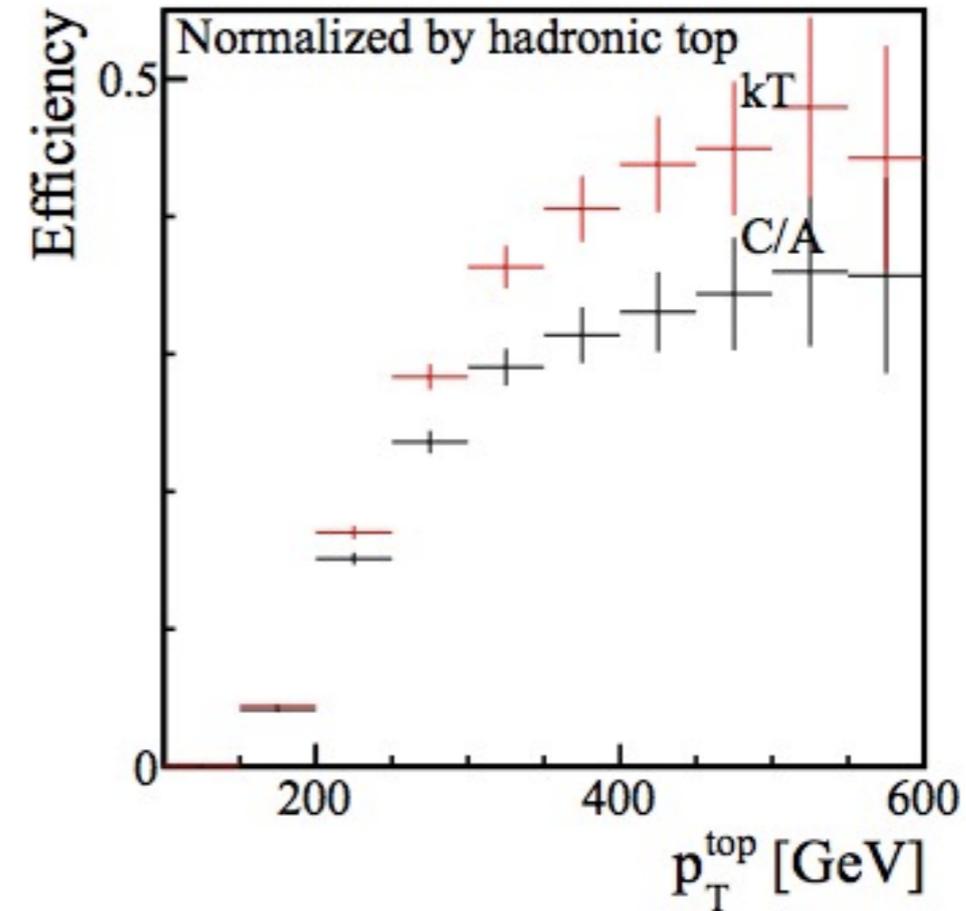
- ▶ Efficiency of $\sim 50\%$ for identifying boosted top quarks up to 2 TeV
- ▶ Mistag rate is \sim few percent level across this p_T range
- ▶ Used in several searches
 - ▶ Example: $Z' \rightarrow t\bar{t}$



HEP Top Tagger

Plehn, Spannowsky, Takeuchi,
arXiv:1111.5034

- ▶ Larger cone size used ($R = 1.5$)
 - ▶ Increases efficiency at low p_T
- ▶ Clusters jet into subjets, looks for top and W candidates
 - ▶ Using subjet mass combinations
- ▶ Used in both ATLAS and CMS



N-Subjettiness

- ▶ Additional signal discriminating power could be obtained from N-subjettiness
 - ▶ J. Thaler, K. Van Tilburg, arXiv:1011.2268

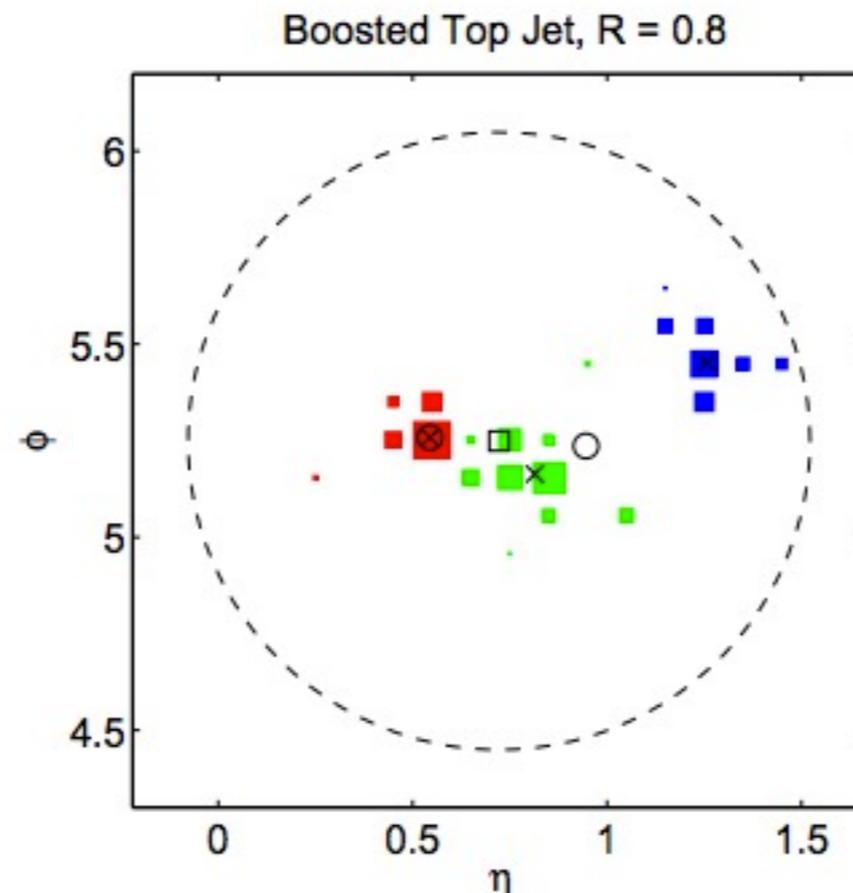
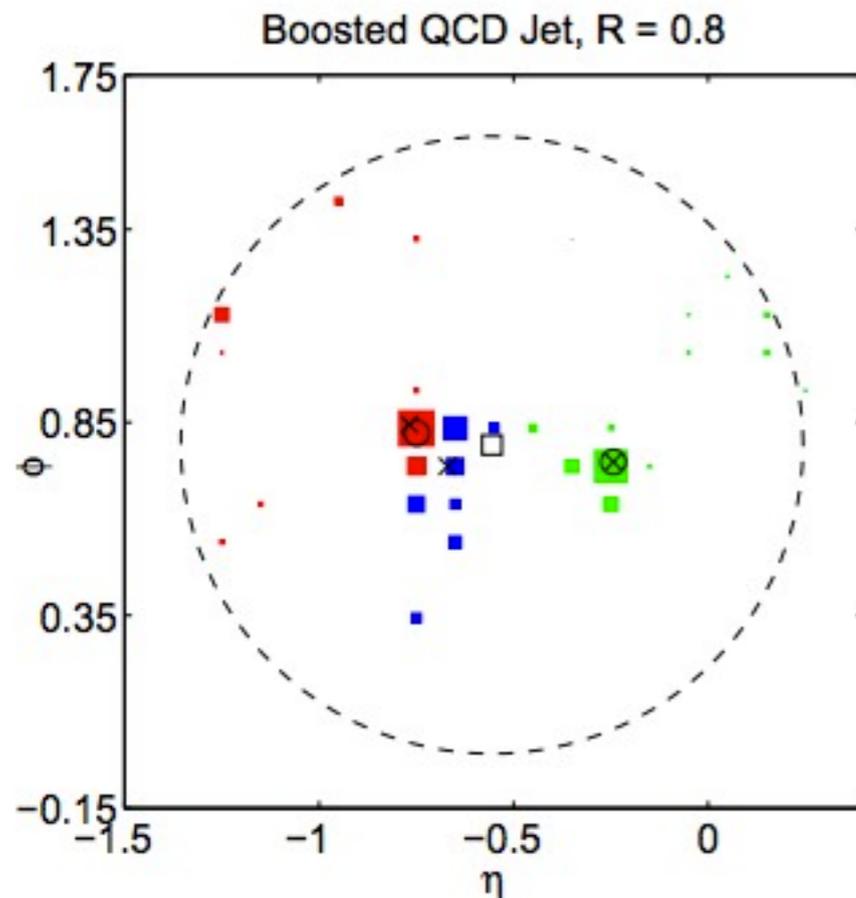
- ▶ Determines the consistency of the particles in the jet with N number of subjets
- ▶ Requires clustering the jet into N exclusive subjets

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \cdot \min(\Delta R_{1,k}, \dots, \Delta R_{N,k})$$

Normalization factor

Jet constituent index

Subjet index



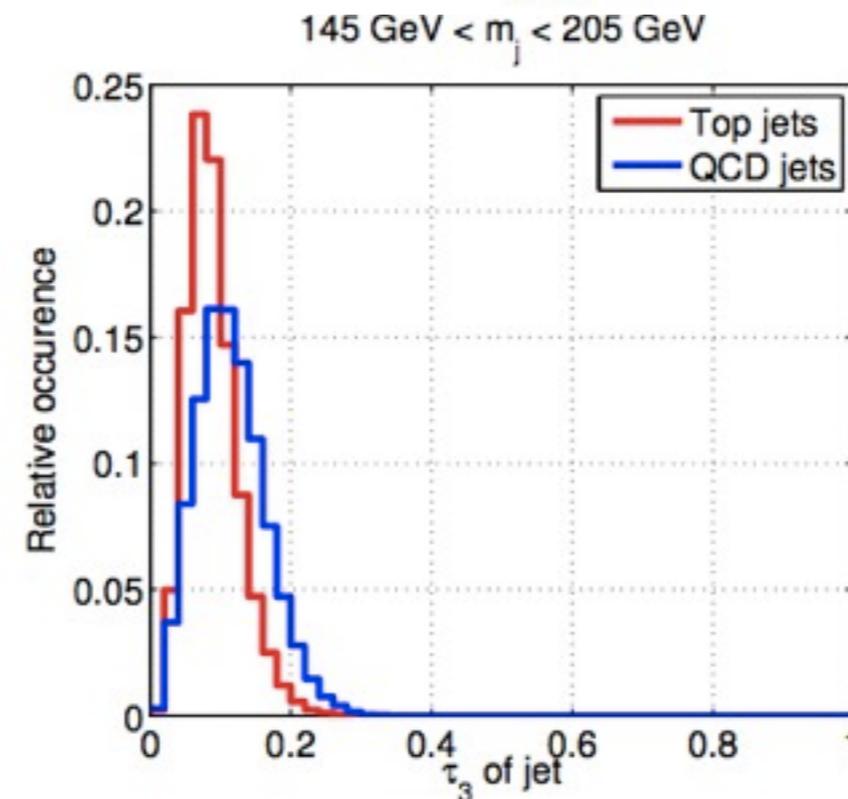
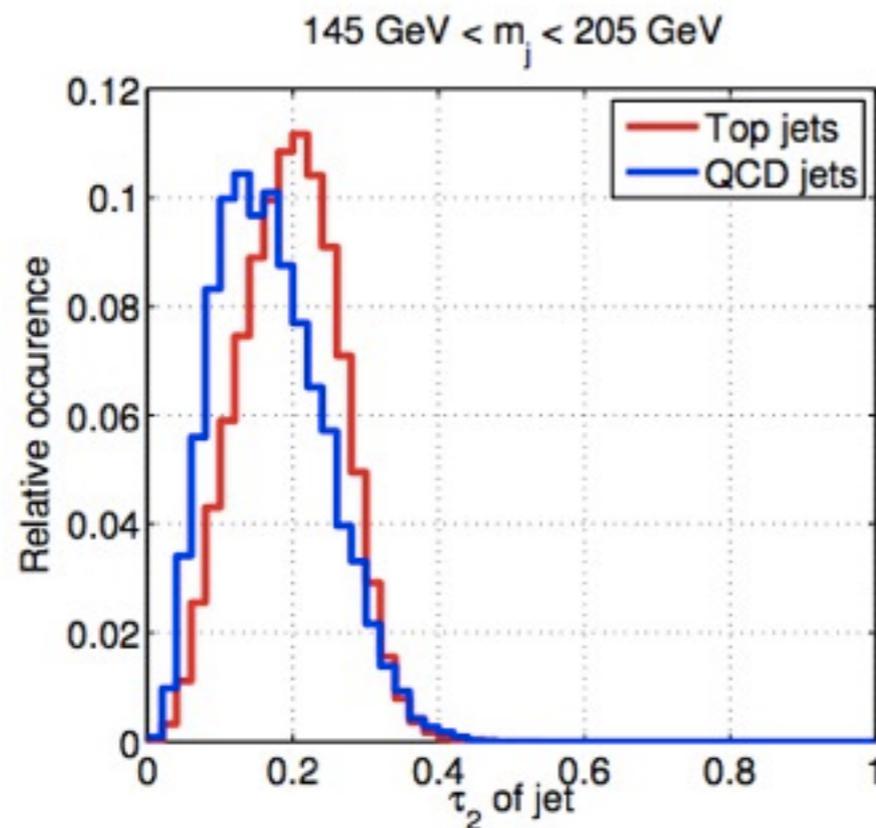
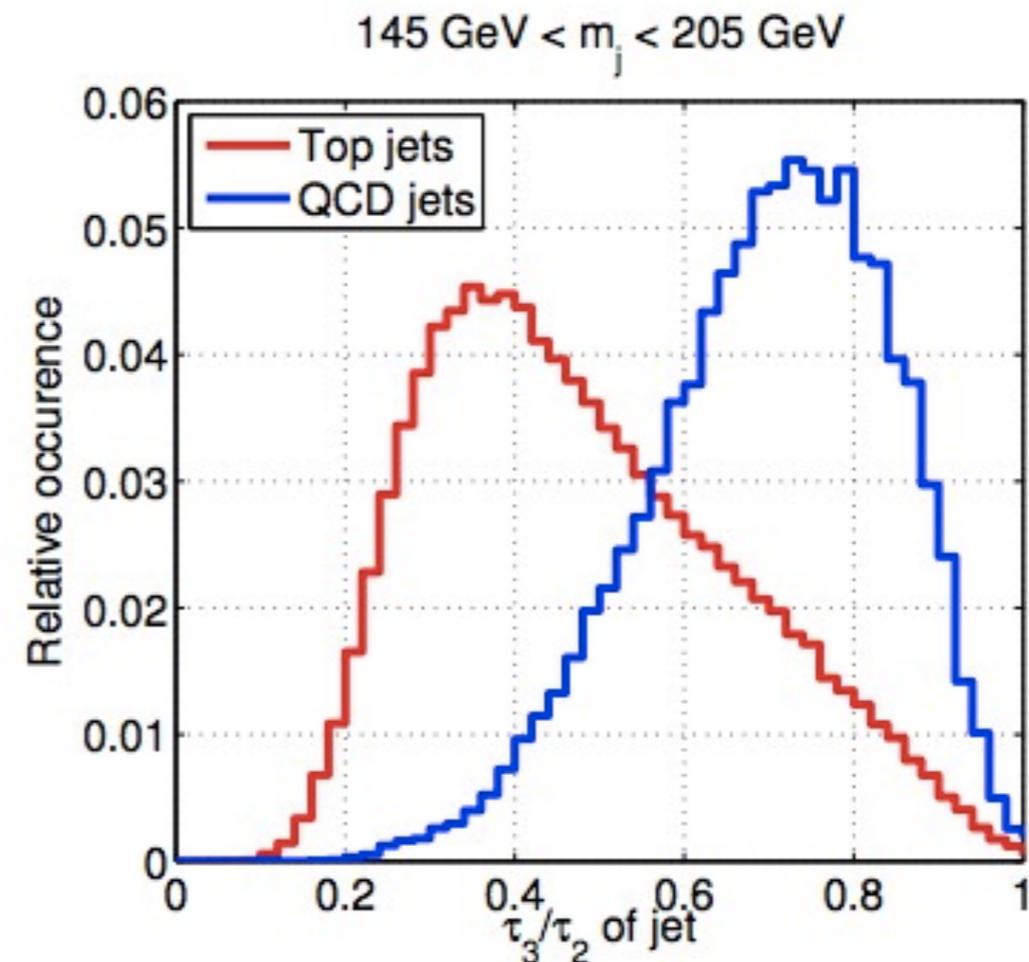
Subjet positions after clustering into N subjets:

- N = 1
- N = 2
- × N = 3

From arXiv:1011.2268

N-Subjettiness

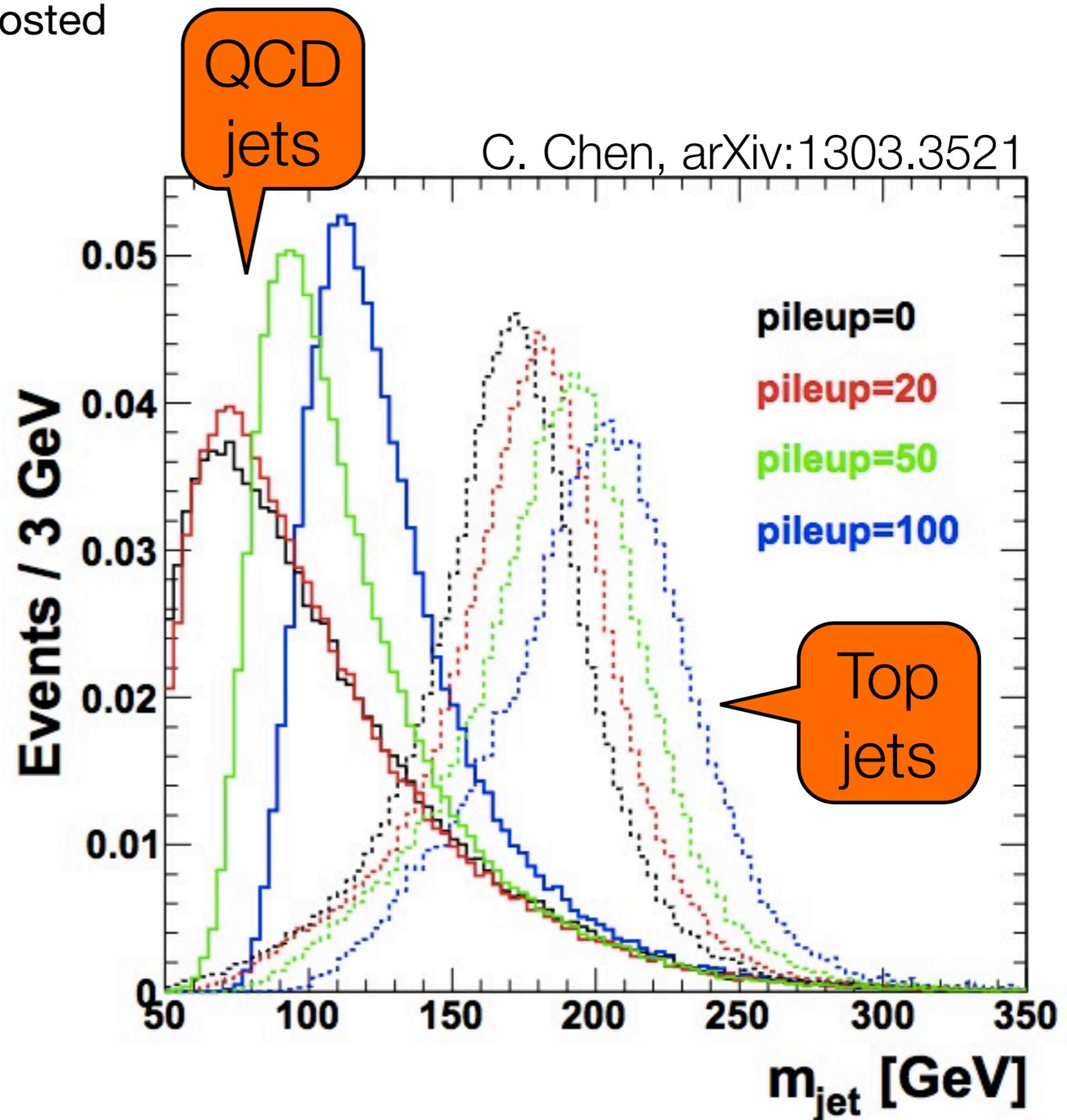
- ▶ Ratios more useful than individual values
 - ▶ τ_2 / τ_1 can distinguish W jets
 - ▶ τ_3 / τ_2 can distinguish top jets
- ▶ Jets here have $p_T > 300$ GeV, mass in top mass window
- ▶ Good discrimination power between top and QCD!



Pileup Effects

- ▶ Crucial to distinguish genuine boosted tops from multijet backgrounds
- ▶ Detailed study by C. Chen:
- ▶ With large amounts of pileup, contamination of QCD jets is large
 - ▶ For 100 pileup events, 90% of QCD jets have 3 subjets

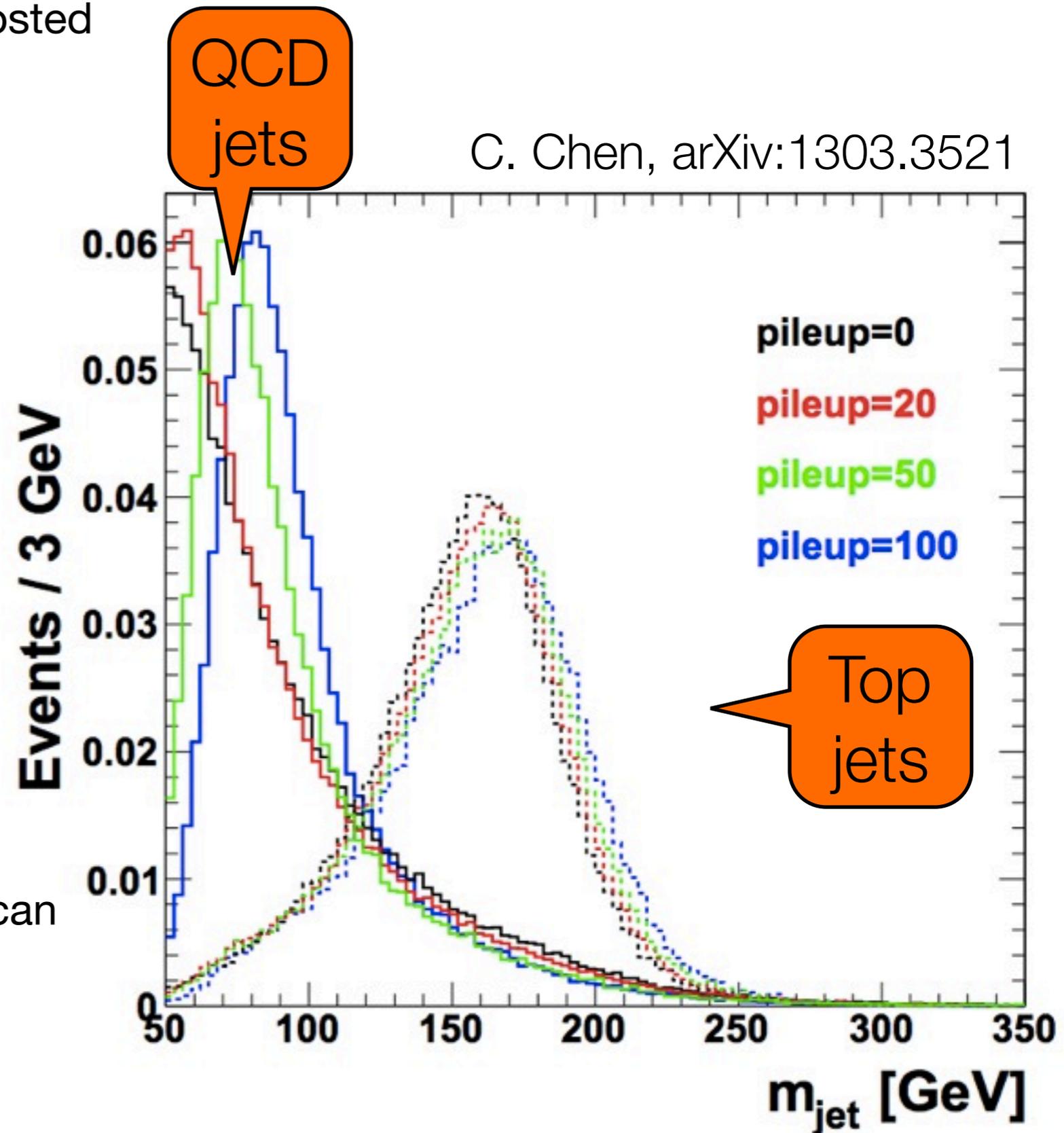
C. Chen, arXiv:1303.3521



Pileup Effects

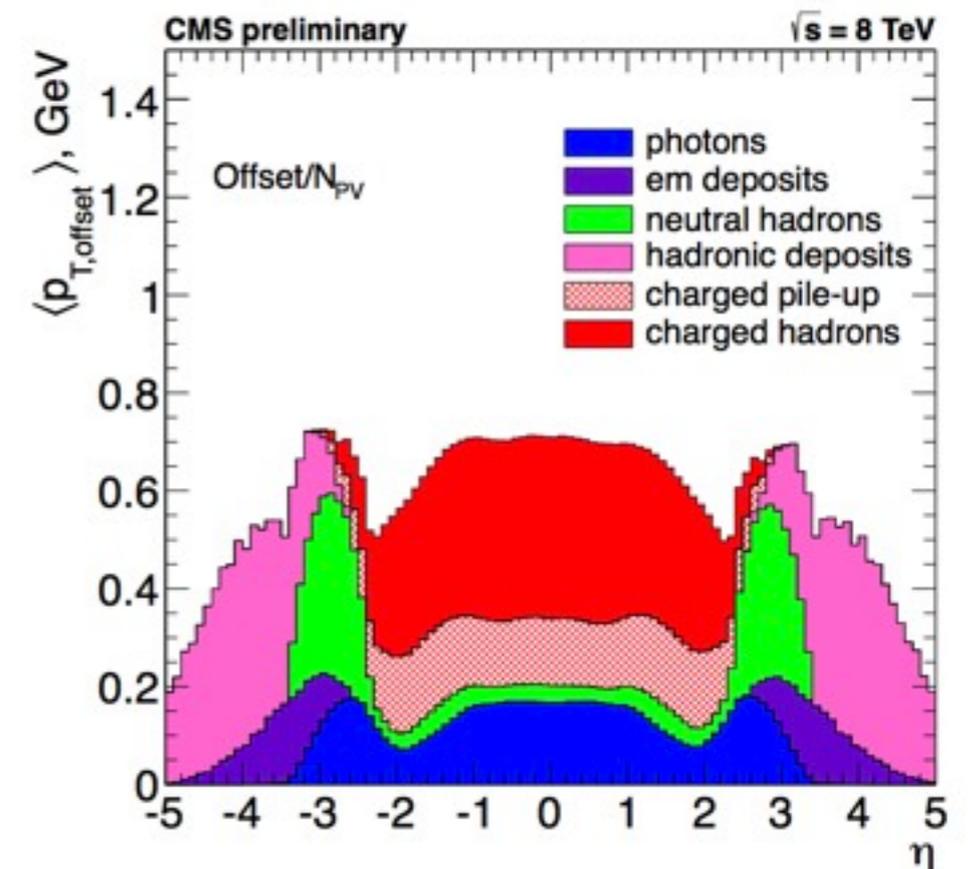
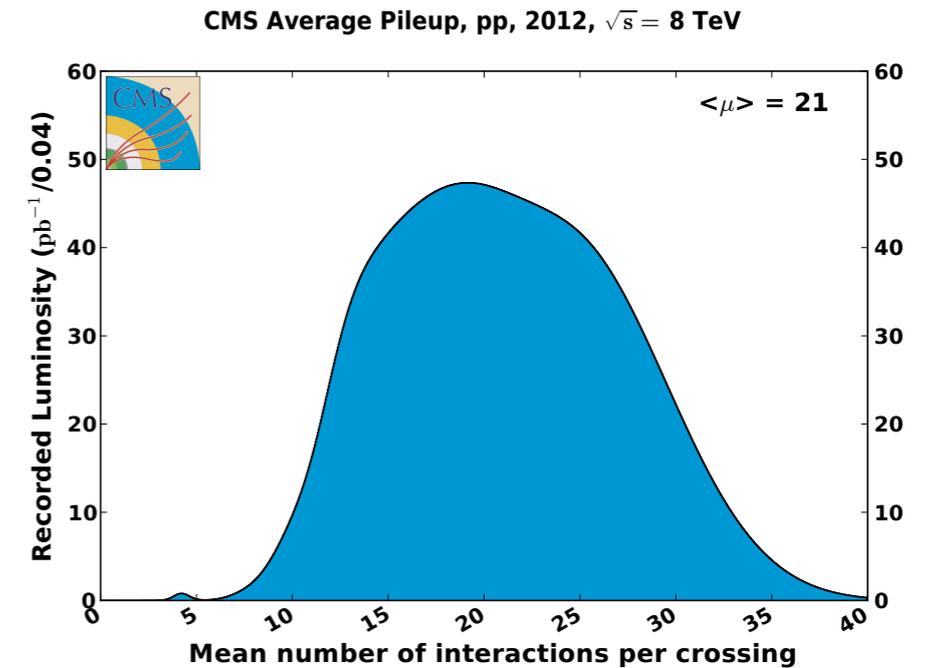
- ▶ Crucial to distinguish genuine boosted tops from multijet backgrounds
- ▶ Detailed study by C. Chen:
- ▶ With large amounts of pileup, contamination of QCD jets is large
 - ▶ For 100 pileup events, 90% of QCD jets have 3 subjets
- ▶ Reclustering in the jet rest frame can improve discrimination!
 - ▶ Calculate jet mass from subjets

C. Chen, arXiv:1303.3521



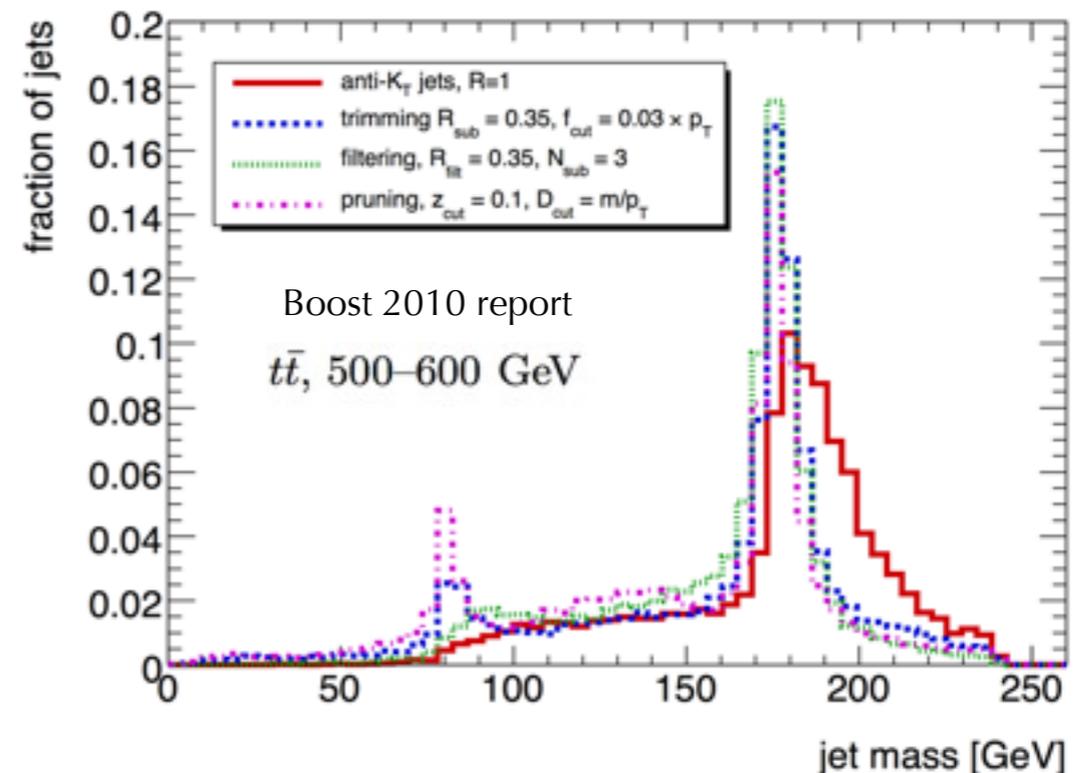
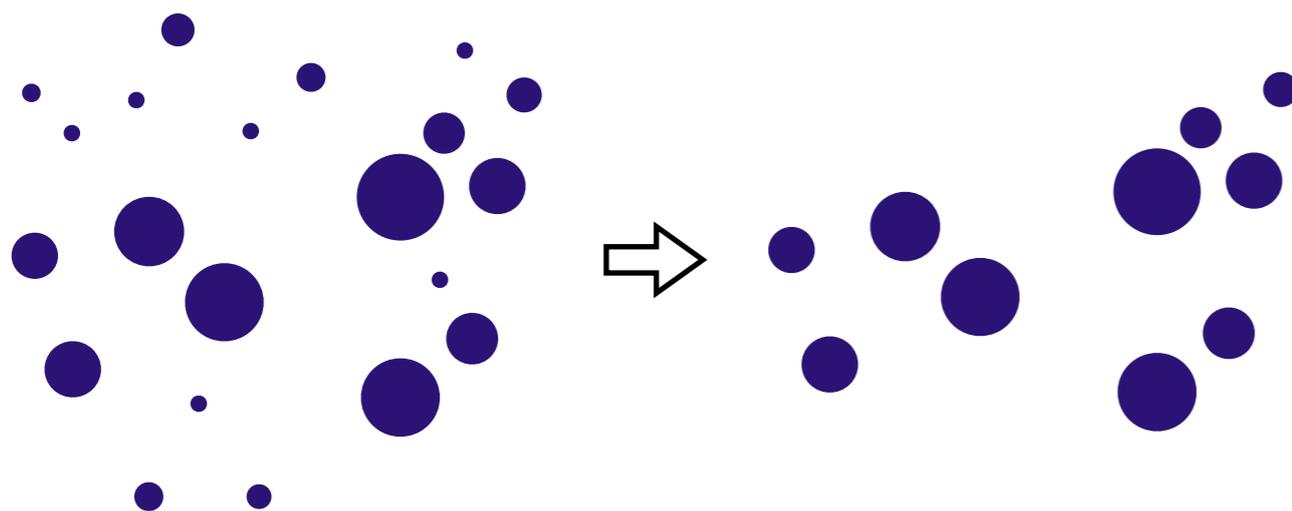
Pileup and boosted tops

- Future LHC: $\langle \text{PU} \rangle = 50-140$
- Top tagging observables are influenced by pileup
 - Fat jets \rightarrow large jet area
 - Jet mass, number of subjects increases
- Most top tagging algorithms have built in pileup mitigation (jet grooming) in addition to the standard PU corrections
- Snowmass study: How well do these techniques work at very high PU?



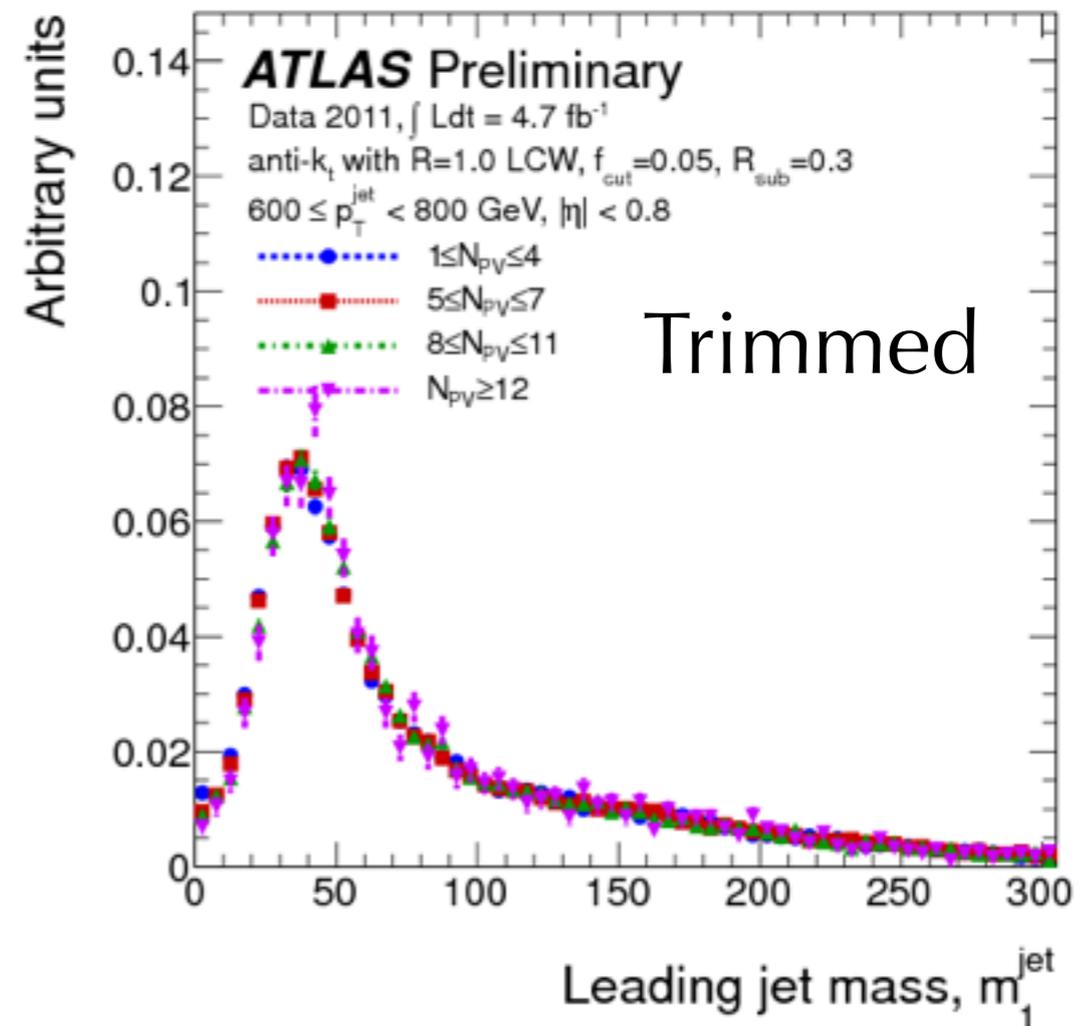
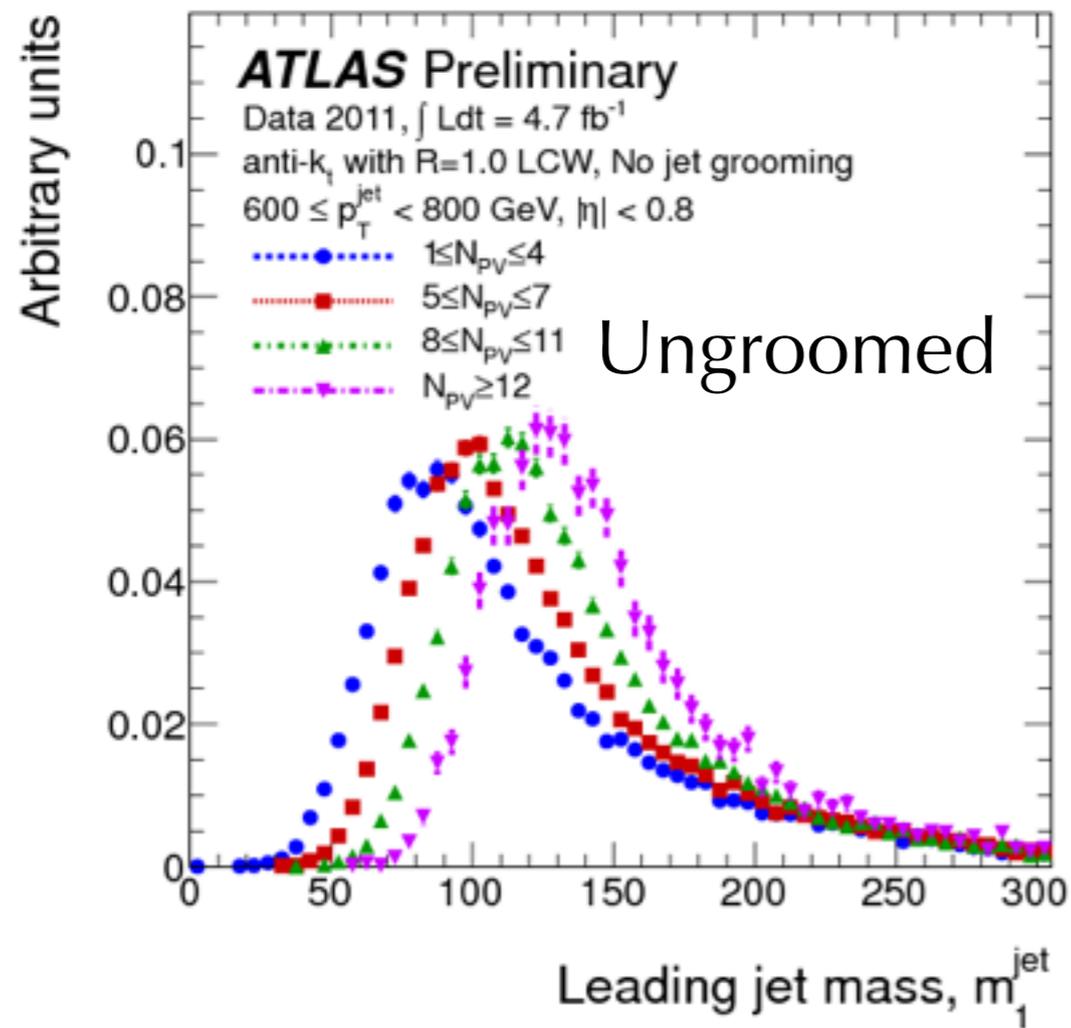
Jet Grooming

- Reduces the jet area by removing soft, large angle particles
- Pruning (Ellis, Vermillion, Walsh)
 - Recluster the jet. Don't merge low p_T , large angle constituents.
- Trimming (Krohn, Thaler, Wang)
 - Recluster the jet using a small distance parameter. Remove subjects with low p_T .
- Filtering (Butterworth, Davison, Rubin, Salam)
 - Recluster the jet using a small distance parameter. Keep only the n hardest subjects.



Pileup mitigation - QCD jets

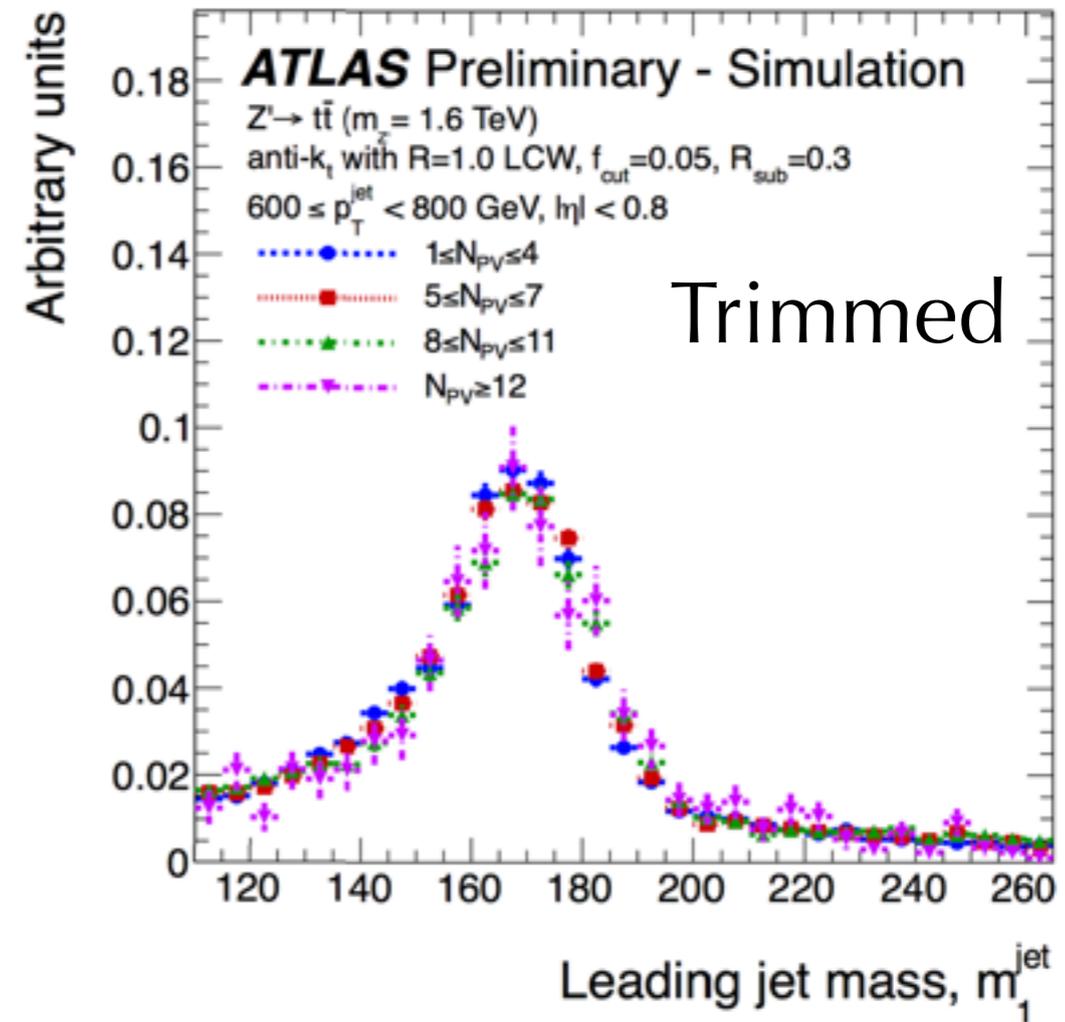
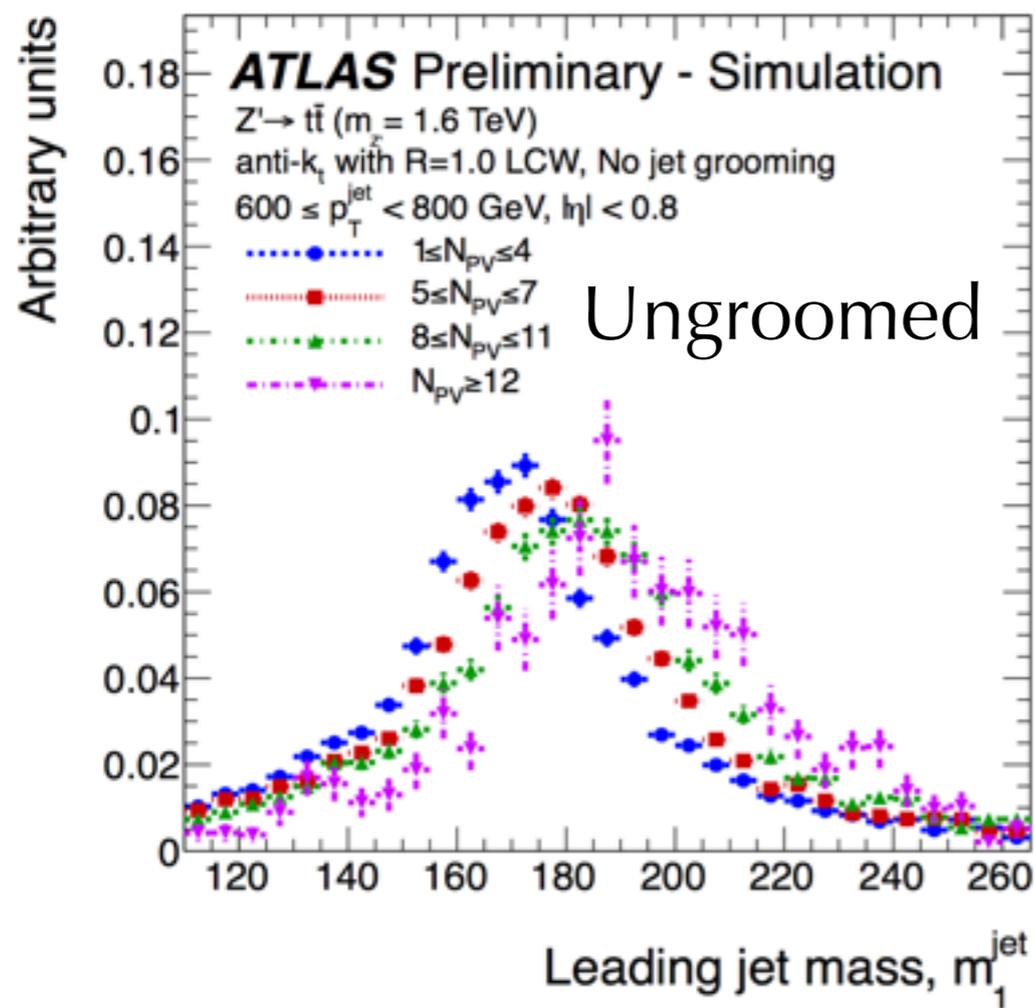
ATLAS-CONF-2012-066



- Groomed jet mass is more stable with increasing PU
- Groomed QCD jets have a lower mass \rightarrow smaller background for top tagging

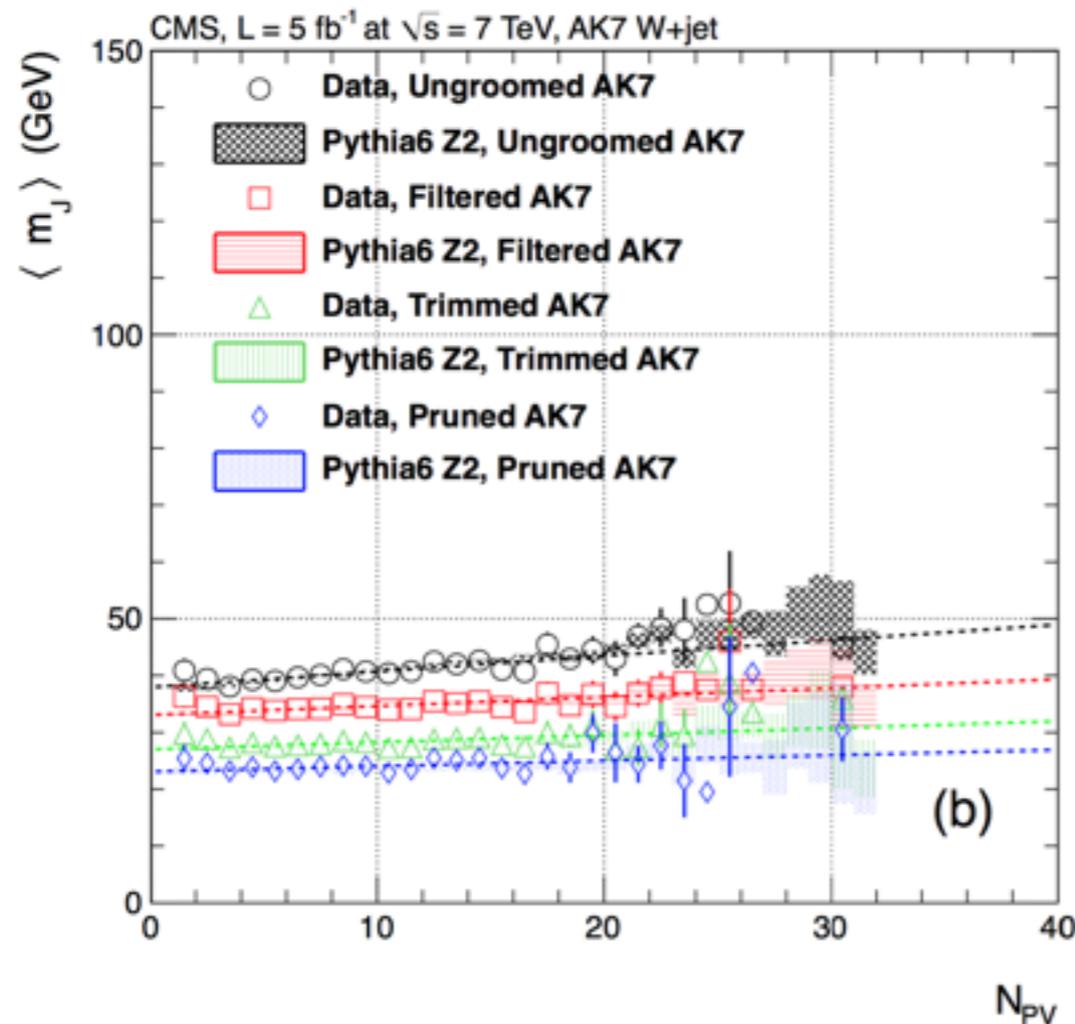
Pileup mitigation - top jets

ATLAS-CONF-2012-066



- Groomed top jet mass is more stable with increasing PU
- Sharper mass peak

Pileup mitigation - grooming



CMS SMP-12-019

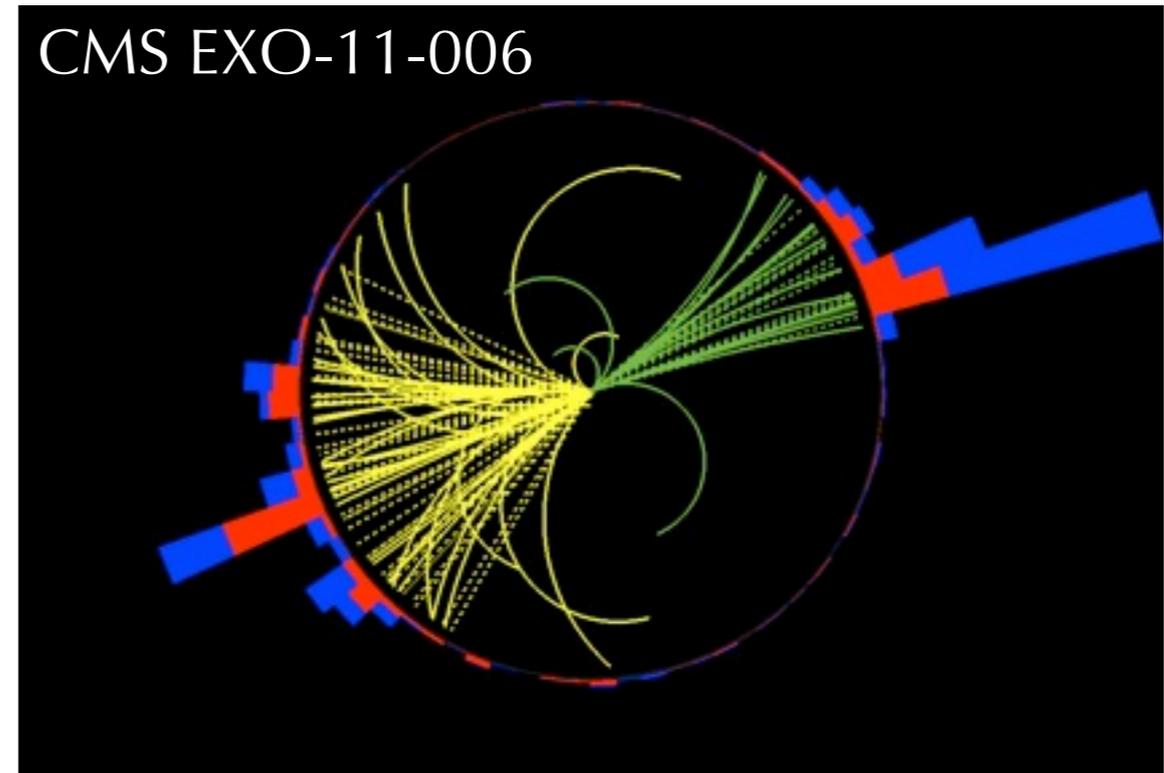
Ratio of slopes	Measured	Expected
$s_{0.7}/s_{0.5}$	2.7 ± 0.9 (stat.)	$(0.7/0.5)^3 = 2.74$
$s_{0.8}/s_{0.5}$	3.3 ± 1.0 (stat.)	$(0.8/0.5)^3 = 4.10$
$s_{0.8}/s_{0.7}$	1.2 ± 0.2 (stat.)	$(0.8/0.7)^3 = 1.49$

Jet R	Clustering algorithm	s_R (GeV/PV)
AK5	ungroomed	0.10 ± 0.03 (stat.)
AK7	ungroomed	0.28 ± 0.03 (stat.)
AK7	filtered	0.16 ± 0.02 (stat.)
AK7	trimmed	0.12 ± 0.04 (stat.)
AK7	pruned	0.10 ± 0.05 (stat.)
AK8	ungroomed	0.33 ± 0.03 (stat.)

- Larger jets are more affected by PU
 - Pileup contribution to average jet mass $\propto R^3$
- Groomed jet mass is more stable with increasing PU

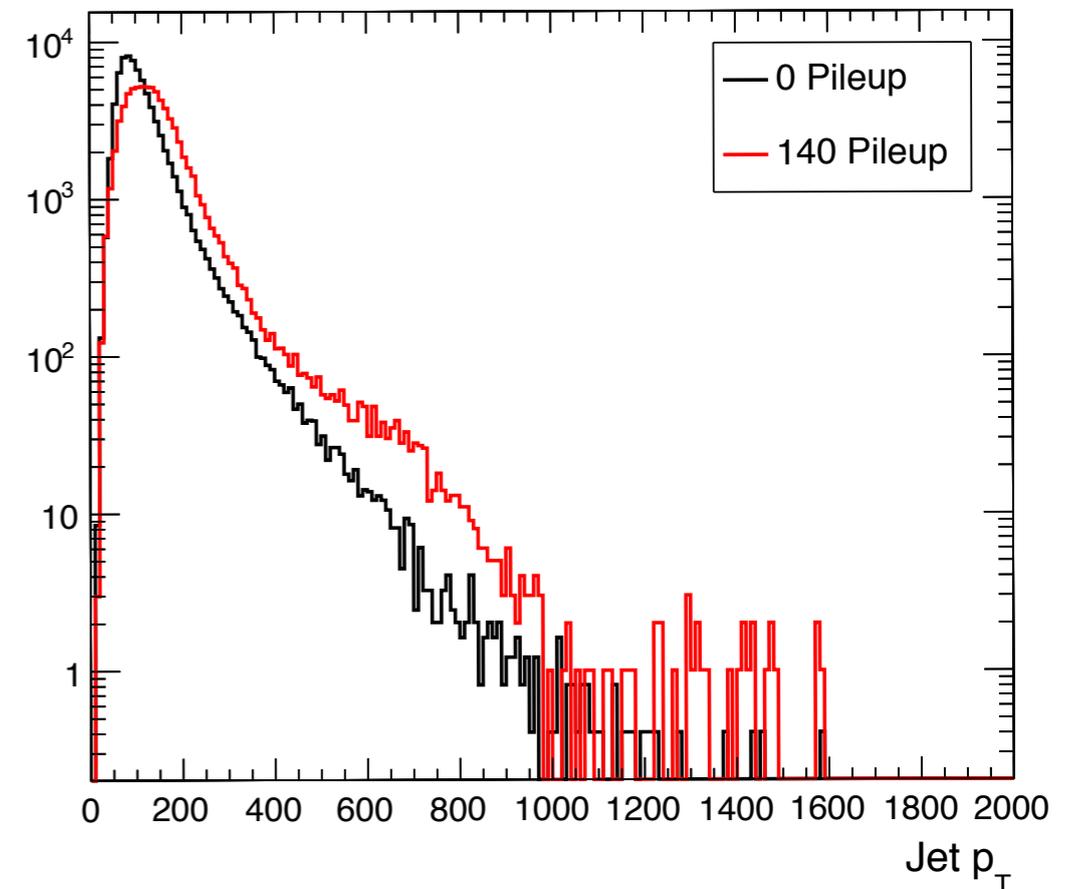
Top tagging at very high p_T

- Detector segmentation limits our ability to resolve subjets from high p_T tops
- We have methods to improve this resolution:
 - Take advantage of ECAL granularity, track jets, particle flow
- As the top boost increases eventually we will reach tracking limits
 - Very small angles between tracks will lead to decreased track efficiency
 - Also CPU limited



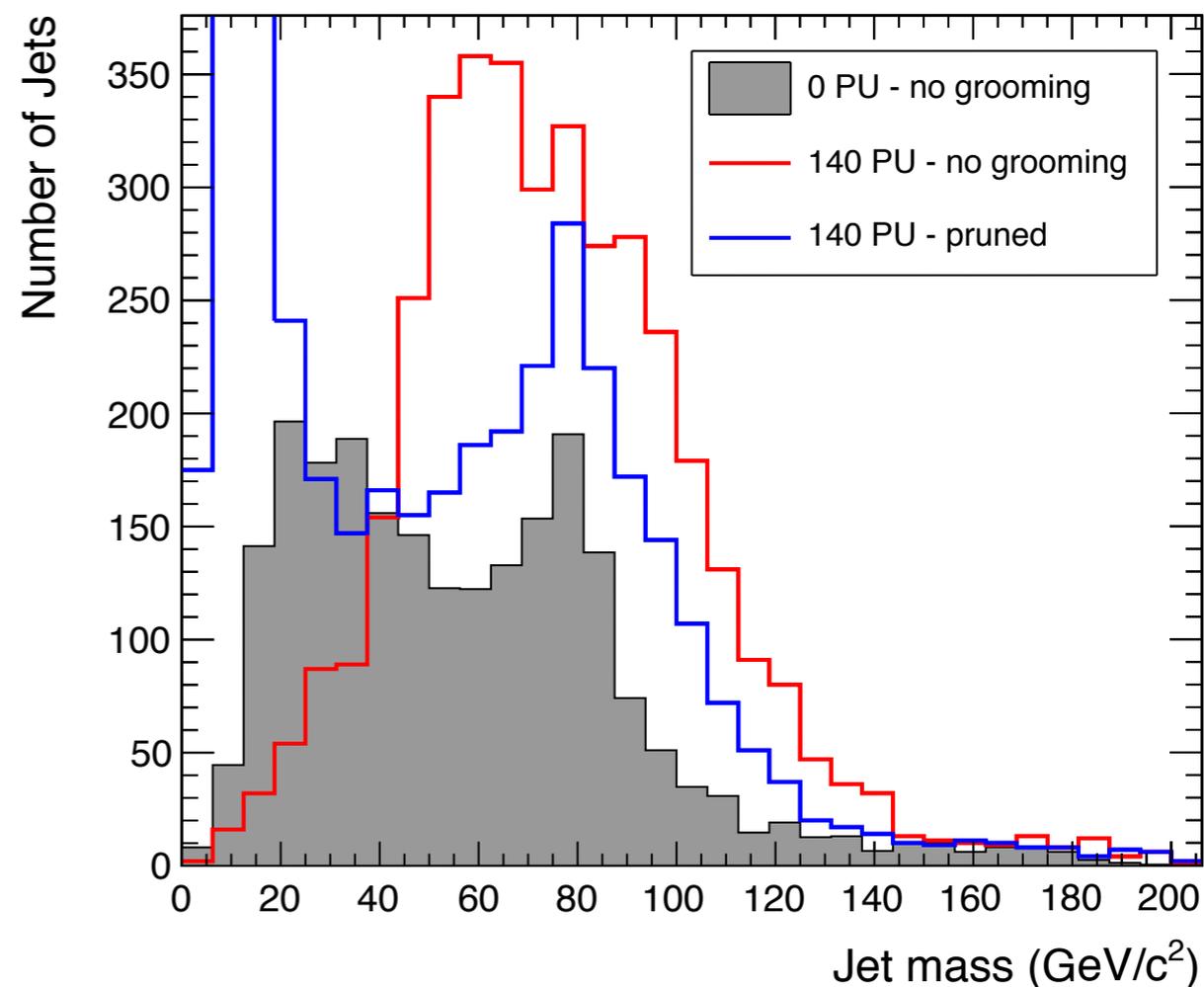
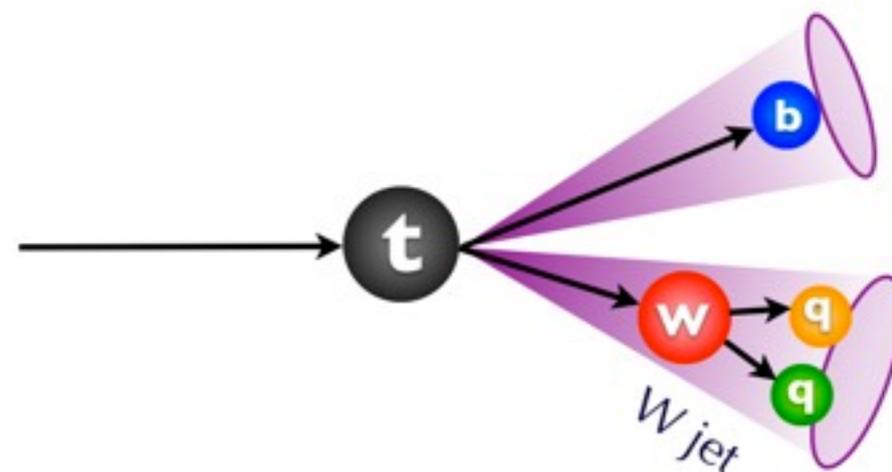
Snowmass Studies

- Using “preliminary” Snowmass samples (<http://red-gridftp11.unl.edu/>)
 - TTbar 13TeV - 0 PU and 140 PU
 - Delphes CMS-like detector
 - Jets reconstructed from EFlow objects
 - Towers, tracks and muons
 - Re-cluster jets with FastJet
 - Cambridge Aachen 0.5
 - Prune jets then find subjets



Jet Mass

- Select high p_T leading jets ($p_T > 300$)
- W peak is visible in 0 PU TTbar jet mass distribution
 - We need improved high p_T statistics and larger jets to reconstruct top jets
- Peak washed out in 140 PU sample
- Pruning recovers the peak



Conclusions

- Questions to answer:
 - What are the current tagging efficiencies and mistag rates of current top tagging algorithms?
 - How does top tagging perform at very high p_T ?
 - How does top tagging perform in high pileup environments?

Additional Material

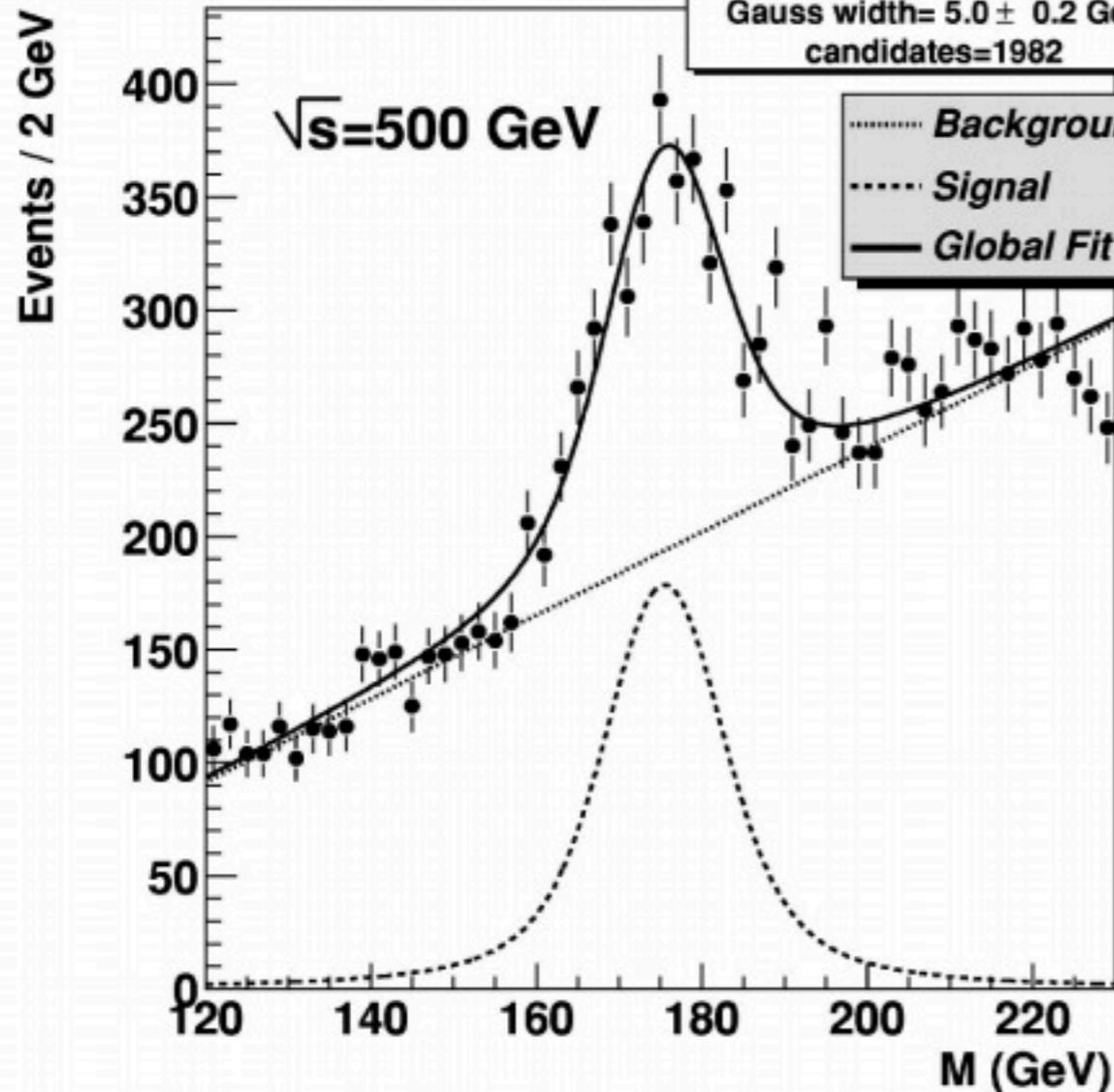
Linear Collider

PRD 67, 074011 (2003)

- ▶ Studies from S. Chekanov, V. Morgunov
- ▶ Context of an $e^+ e^-$ collider at center of mass energy 500/800 GeV

- ▶ Fully hadronic decay resulting in nominally 6 jets
- ▶ Increasing energy gives degraded resolution
 - ▶ Decay products overlapping

BRW \oplus Gauss



BRW \oplus Gauss

